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## TECHNOLOGY OF LIGHT METALS

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# TECHNOLOGY OF LIGHT METALS

by

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ALUMINIUM INDUSTRIE-A.G., CHIPPIS (SWITZERLAND)

Translated from the First  
Swiss Edition by  
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## PREFACE

The art of working the heavy metals has behind it a thousand years of experience and knowledge; the light metals have had their introduction to the workshop only in the present century. Yet their applications are extending all the time to new industrial fields, but the necessary knowledge of the working of the light metals is slow to keep pace with their development.

For the practical man, required items of information that may be widely distributed in the technical abstracts are often not easy to track down, and hitherto available textbooks on the technology of aluminium which might be useful to the process technologist, supervisor or operative in the Works are becoming years out of date. There is now a widespread need for another textbook on the technology of the light metals which covers the whole field of working and includes all the latest developments of recent years.

In the four German and one English editions of the author's earlier work, "The Technology of Aluminium and its Light Alloys", the working of aluminium was solely covered. In this present work, "Technology of Light Metals", the fabrication of magnesium and its alloys has also been included. In view, however, of the more restricted use of magnesium in world commerce, which is only about 10% of that of aluminium, the space devoted to magnesium has been restricted accordingly, but the more important points in the manufacture have been suitably covered. As light metals other than aluminium and magnesium have yet acquired no importance in commerce, they are not dealt with in this work.

The designation of the various alloys presents some difficulty. As, however, all the most important alloys have been included in standards by the Verein Schweizerischer Maschinen-Industrieller (Swiss Machinery Manufacturers' Association), called VSM for short, the VSM symbolic designations have in general been adopted in this text in addition to the trade names commonly used in Switzerland. A table of comparison of trade names in other countries is included as being of special interest.

The alloy trade names "Avional", "Anticorodal", "Aluman", "Peraluman", "Silafont", "Perunal", and "Unifont" are trade-marks belonging to the Aluminium-Industrie AG. To avoid tedious repetition, reference is not made to this everywhere in the text.

The treatment of aluminium production and the theory of alloys has

been modified only as far as has been necessary for comprehension of the correct fabricating practice. As formerly, debatable theoretical considerations are avoided as much as possible and practical data are given for preference.

The requirements that the author's tutorial and practical experience have shown to be desirable in such a textbook have been embodied throughout.

A bibliography of the more important references in the literature on the subject is included as an appendix. As a very complete bibliography including patent references was given in the fourth German edition, it is felt that a full repetition can be dispensed with here.

The author begs to express his thanks to all those friends who have contributed to the work with information, illustrations and assistance, especially to the Aluminium-Industrie-A.G. Chippis for their permission to publish the data from numerous laboratory and works tests. The author would also gratefully acknowledge the valuable assistance of Messrs HERRMANN, ZURBRÜGG, IRMANN, HUG, KOCHERHANS, VON BURG, FICHTER, and Miss KUMMER. He is particularly indebted to Mr. A. J. FIELD, who after having translated the author's "Technology of Aluminium and its Light Alloys" in 1936, has accepted again to translate the text into English. Owing to the great comprehension Mr. FIELD had for the original text and his perfect knowledge of the German language, an English text of equal value has been created in spite of the high difficulties which occur in the correct translating of technical terms. The author wishes to express his special thanks to him.

The author will always be glad to receive suggestions for additions or improvements to the work that might be incorporated in a new edition, and will appreciate objective criticism.

Neuhausen, May 1949

A. VON ZEERLEDER

## PREFACE TO THE ENGLISH EDITION

As in the case of Dr. VON ZEERLEDER's previous textbook "The Technology of Aluminium and its Light Alloys", a translation into English was undertaken as a useful piece of work that would be of benefit to those readers in English-speaking countries who are interested in the manufacture and use of aluminium and magnesium and their alloys, and who will want to have ready recourse to an up-to-date textbook by so eminent an authority as Dr. VON ZEERLEDER.

The aim of the translator has been to render the author's meaning faithfully and to present it in acceptable style, and with the use of recognized terminology.

In this there is some complication in that there are sometimes differences between British and American expressions, and indulgence is requested where reference has not been made to both. In order that readers in both hemispheres may be able to read the relevant quantities in the units to which they are accustomed, temperatures are presented in both Centigrade and Fahrenheit, and stress units in both tons and pounds per square inch.

As four years have elapsed from the completion of the German manuscript to the publication of the English edition, it has been possible to make references in the latter to several important new developments which did not appear in the German edition.

Falkirk, May 1949

A. J. FIELD





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## PART I. GENERAL

### CHAPTER I: HISTORY AND PRODUCTION

#### 1. INTRODUCTION

Aluminium and magnesium are the only light metals which are widely used in industry in the pure form or as the bases of alloys. The importance of the two metals is shown by the tonnages of the world production which due to the demands for war material amounted in 1943 to 2 000 000 tons of aluminium and between 200 000 and 300 000 tons of magnesium. The ratio of these tonnages of about 10 to 1 which has held good steadily with little deviation over the last 20 years can be taken as a reliable indication of the present relative industrial importance of the two metals. As the term "light metals" connotes, their outstanding characteristic is their light weight or low specific gravity. There is at the present time no standard value of this property recognized as a qualification for the title "light metal". The upper limit to qualify for inclusion in the light class lies in the range of specific gravity 3 to 5. REGELSBERGER's<sup>1</sup> figure of 3.8, or say 4, can be taken as a reasonable upper limit of specific gravity for the light class, since there is no commercially important aluminium- or magnesium-base alloy with a higher specific gravity than 4. In Table I are listed all the light metallic elements with their atomic weights, specific gravities and annual production, which last figure gives an indication of their commercial importance.

TABLE 1  
THE LIGHT METALLIC ELEMENTS

Element	Atomic weight (1940)	Specific gravity in the solid state	Annual production (approximate, tons)	Year
Lithium . . . . .	6.94	0.53	20	1934
Potassium . . . . .	39.10	0.86	very small	1934
Sodium . . . . .	23.00	0.97	20 000	1939
Rubidium . . . . .	85.48	1.52	very small	1938
Calcium . . . . .	40.08	1.55	200	1945
Magnesium . . . . .	24.32	1.75	235 000	1944
Beryllium . . . . .	9.02	1.85	500	1942
Caesium . . . . .	132.91	1.87	very small	1945
Strontium . . . . .	87.63	2.60	very small	1934
Aluminium . . . . .	26.97	2.70	1 650 000	1944

<sup>1</sup> REGELSBERGER, *Chemische Terminologie der Leichtmetalle*, p. 2.

## 2. THE PRODUCTION OF ALUMINIUM

a. *Historical*

If we consider the distribution of the metals in the earth's crust, as shown in Table 2, we see that aluminium at 7.5% stands first among the useful metals. While gold, silver and copper were known about 5000 B.C. and tin, lead and iron as well as the copper-tin alloy, bronze, were discovered between 3000 and 3500 B.C., it is striking that aluminium, the most widespread of all metals, only came to light in 1825.

TABLE 2

PERCENTAGE OF METALS IN THE EARTH'S CRUST, WITH HEAT OF OXIDATION AND ELECTRODE POTENTIAL AGAINST HYDROGEN

Metal and Symbol		Percentage in earth's crust	Heat of oxidation kcal per g. atom	Normal potential against hydrogen volts
Silicon	Si...	25.8	191 (crystal)	$\pm 0$ (approx.)
Aluminium	Al...	7.5	190	-1.45
Iron	Fe..	4.3	64 (FeO)	-0.43
Calcium	Ca..	3.4	152	-2.5
Sodium	Na.	2.6	50	-2.72
Potassium	K.	2.4	43	-2.95
Magnesium	Mg..	1.9	144	-1.87
Zinc	Zn..	0.004	85	-0.76
Strontium	Sr..	0.02	139	-2.7
Copper	Cu..	0.01	37 (CuO)	+0.35
Tin	Sn..	$6.10^{-6}$	138 (SnO <sub>2</sub> )	-0.15
Gold	Au...	$2.10^{-8}$		+0.99



Fig. 1. Oersted 1777—1851.

If we consider the heats of oxidation of the metals in Table 2, we perceive how much greater is the affinity of aluminium for oxygen in comparison with that of the metals known in antiquity, which indicates the much more difficult reducibility of aluminium. It follows from this that aluminium cannot be reduced from its oxide by heating with carbon, as can iron or copper. Even in the heat of the electric arc, in which reduction by carbon is possible, owing to the affinity of aluminium for carbon the metal liberated is strongly contaminated with carbides, which decompose with evolution of

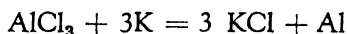
gas on exposure to air, which renders metal produced in this way commercially useless. A more satisfactory method of reduction had therefore to be sought. The first to discover one was Oersted of Den-



Fig. 2. Wöhler 1800—1882.

mark (Fig. 1) who in 1825 described before the Imperial Danish Society for Natural Philosophy, the formation of metallic aluminium by the reduction of aluminium chloride with potassium amalgam. This claim was held in doubt for a long time until the researches of FOGH<sup>1</sup> and also HAAS<sup>2</sup> brought satisfactory confirmatory proof that metallic aluminium can be obtained by the method described by OERSTED.

WÖHLER (Fig. 2) in 1827 improved the chemical reduction process for aluminium by the replacement of potassium amalgam by metallic potassium over which he led aluminium chloride vapour, the reaction being as under:



In the commercial production of aluminium, H. SAINTE-CLAIRE DEVILLE (Fig. 3) (1854) developed a further process, arising from a rational understanding of the reacting materials. DEVILLE replaced the hygroscopic aluminium chloride by the less hygroscopic double sodium-aluminium chloride, and also the costly potassium by the cheaper sodium, to the production of which he devoted special attention. Due to his process, the price of aluminium dropped from £ 53 sterling per pound in 1854 to £ 11 in the following year, and later on to £ 3-12s per pound in 1880.

The visionary enthusiasm of SAINTE-



Fig. 3. Sainte-Claire Deville 1818—1881.

<sup>1</sup> FOGH, Properties of aluminium amalgams, *Det. Kgl. Danske Videnskabernes Selskab* T III, (1921).

<sup>2</sup> HAAS, *Aluminium*, 21 (1939) 822.

CLAIRE DEVILLE, the first to produce aluminium on the commercial scale, is evinced in the conclusion of his address at the London Exhibition of 1862, as follows:

"Aluminium is the intermediate metal between the noble and the base

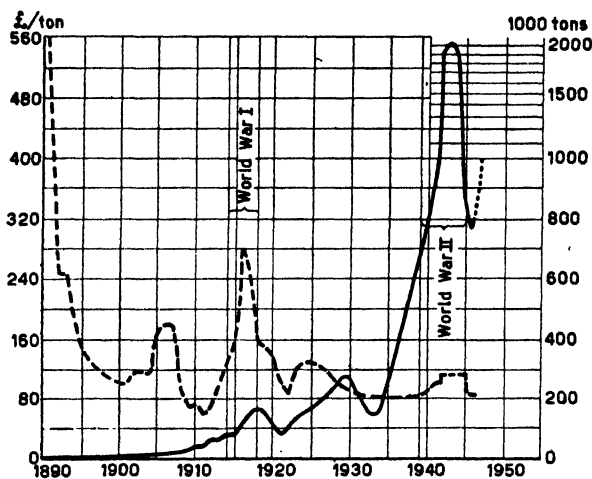


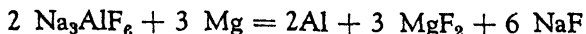
Fig. 4. Market price and world production of aluminium.

metals. This connecting link which was missing in the past, has been haphazardly used in imperfect alloys, which unlike gold and platinum were not unchangeable nor unharmed in the air. It is true that aluminium does not have such complete power of resistance to chemical reagents as is possessed by the noble metals, but none-the-less it is unaffected by air, water, sulphuric acid, nitric acid, or sulphuretted hydrogen, which is not so in the case of iron, copper nor silver. This will mean that aluminium will speedily win for itself in the arts a high place of usefulness with its metallic ring, its high degree of malleability, its capability of being wrought, and its remarkable light weight. I shall be fully satisfied if it is accepted by industry as such an intermediate metal. If the day comes when the ways and means are discovered of separating it at low cost from its ore, clay, the most widespread constituent of the crust of the earth, then it will become the commonest of all metals. Then would my hopes be fulfilled, and I would be happy to ascribe the chief credit to him who produced the first beads of metallic aluminium, the illustrious chemist of Göttingen, WÖHLER". (Here again we see the erroneous belief that WÖHLER and not OERSTED produced the first metallic beads of aluminium).

Mention must next be made of a simultaneous publication in 1854 by the famous German physicist BUNSEN in Poggendorf's Annalen, and a submission by SAINTE-CLAIRE DEVILLE to the Académie des Sciences, of reports on the electrochemical reduction of aluminium. Since at that time however, the electric dynamo had not been invented as a source of electrical energy, the proposal was not put into actual practice.

Beside SAINTE-CLAIRE DEVILLE's aluminium works in Salindres, aluminium was also produced in the works of the Aluminium und Magnesium-

Fabrik at Hemelingen since 1886, where the process made use of magnesium as a reducing agent for cryolite (sodium aluminium fluoride) thus:



The purity of this metal was distinctly lower than that of *SAINTE-CLAIRE DEVILLE*, which was over 98%, the Hemelingen metal running between 90 and 94%, with 5 to 8% Silicon and 1 to 2% iron. Both processes had to be discontinued as uneconomic following the introduction of the modern electrochemical process for aluminium.



Fig. 5. Héroult 1863—1914.



Fig. 6. Hall 1863—1914.

In 1886, *HÉROULT* (Fig. 5) in France and *HALL* (Fig. 6) in America invented simultaneously, but independently of one another, the electrochemical reduction process for aluminium that is still in use today. In his first French patent of April 23rd, 1886, *HÉROULT* described this as follows:

"I claim the discovery of a method for the production of aluminium as described above, which consists in the electrolysis of alumina dissolved in molten cryolite, into which the current is introduced through suitable electrodes, for example through carbon anodes, which are immersed in the bath of molten cryolite, the bath forming the cathode. With this arrangement, the oxygen liberated at the anode causes this to burn, while the metal deposited on the cathode collects gradually at the bottom of the vessel. The cryolite is not consumed and to maintain a continuous deposition of metal

it is only necessary to replace the alumina consumed in the electrolysis".

The drawing which accompanies the patent is illustrated in Fig. 7. HÉROULT soon realized that external heating of the bath was not necessary, as the electric current passing through the bath generated sufficient heat to maintain it at about 1000° C (1832° F). Thus his patent of addition to French Patent 175,711 claims electrolysis without external heating — (see Fig. 8).

HÉROULT first approached the French industrialist PÉCHINEY, who, by reason of the limited commercial outlets which were erroneously anticipated for the high-priced aluminium of SAINTE-CLAIRE DEVILLE, dissuaded him from the production of pure aluminium, and advised him to produce copper-aluminium alloys, the so-called aluminium bronzes. HÉROULT successfully accomplished this with a suitable modification of his electrolytic process.

In the meantime, the firm of J. G. Neher Söhne, who had a forge at the Falls of the Rhine in Switzerland founded in 1810, became interested in HÉROULT's patents. Owing to foreign competition the operation of the ironworks had become unprofitable and the firm was seeking for a new application for their water power. This,

they foresaw, would be abundantly obtainable with the electrochemical aluminium



Fig. 9. Col. Huber-Werdmüller  
1836—1915.

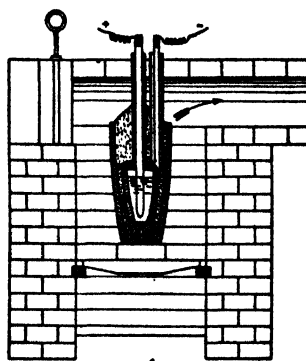


Fig. 7. Drawing of the first aluminium electrolytic reduction cell with external heating, Héroult's French patent 175711, 1886.

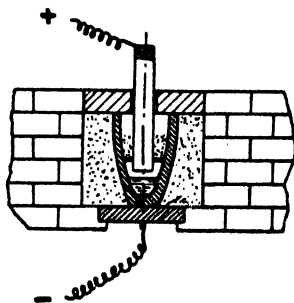


Fig. 8. Drawing of the improved aluminium cell without external heating—Addition to French patent 175711.

process. On the 31st October 1887, the Swiss Metallurgical Company was floated with a capital of 200 000 francs (£ 8 000) with the object of trying out the Héroult process. Only one year later on the 12th November 1888, after the completely successful conclusion of the pilot test, this Company was converted, with the participation of other companies into the Aluminium-Industrie-Aktien-Gesellschaft with a capital of 10

million francs (£ 400 000), a considerable sum at that time. The management was in the hands of Colonel HUBER-WERDMÜLLER (Fig. 9), Chairman, DR. MARTIN SCHINDLER (Fig. 10) and DR. MARTIN KILIANI (Fig. 11) Managing Directors.



Fig. 10. Dr. Martin Schindler  
1858—1927.

Professor TETMAJER, at that time director of the Eidgen. Material-Prüfungsanstalt (Swiss Institution for Testing Materials) the Aluminium- Industrie-Aktien-Gesellschaft investigated and developed different aluminium alloys which could be employed as materials of construction. At first the chief user of the metal was the cooking utensil industry which made full use of its good working properties, heat conductivity, chemical resistance to attack, as well as its light weight. The first commercial application of aluminium appears to be a theodolite made of 98% pure metal by W. and L. E. GURLEY in the U.S.A., which was in service until 1909 and has since occupied a place of honour in this firm's museum. In 1893 a statue of Eros, cast in aluminium, was placed in Piccadilly Circus, London, and still stands today in that damp and corrosive

The Aluminium-Industrie-Aktien-Gesellschaft built firstly the aluminium reduction works at the Falls of the Rhine, Switzerland, of 4000 kW. In addition to this they built a works in Rheinfelden in 1897, one at Lend in 1898, and their big works at Chippis in 1905. The development of this Company is described in their jubilee book "The history of the Aluminium-Industrie-Aktien-Gesellschaft Neuhausen, 1888—1938" (2 volumes).

After the electrochemical reduction process was established and greater quantities of aluminium were available at about £ 120 per ton, development of markets for the new metal became the next objective. In association with



Fig. 11. Dr. Martin Kiliani 1858—1895.





Fig. 12. Turret roofed with aluminium sheeting in Steckborn, erected 1898, dismantled 1931.

air. An analysis of the metal of this statue showed 99.1% Al, 0.27% Fe, 0.6% Si, 0.01% Cu. The high corrosion resistance of aluminium led early to its use for roofing. The oldest example is the dome of the church of San Gioacchino in Rome, which was roofed in 1897 with Neuhausen aluminium and is still in good condition. A year later, in 1898, a turret on a house in Steckborn (Fig. 12) was roofed with aluminium, the impurities being 0.5% Si, 0.5% Fe, 0.08% Cu. In the course of a renovation of the house in 1931, the supposedly zinc roof was taken down in a still unimpaired condition, and not until the scrap metal merchant handled the metal from the roof was it identified as aluminium. The condition of the sheets was such that they could have continued in service as roofing material for an indefinitely longer time. It is therefore not

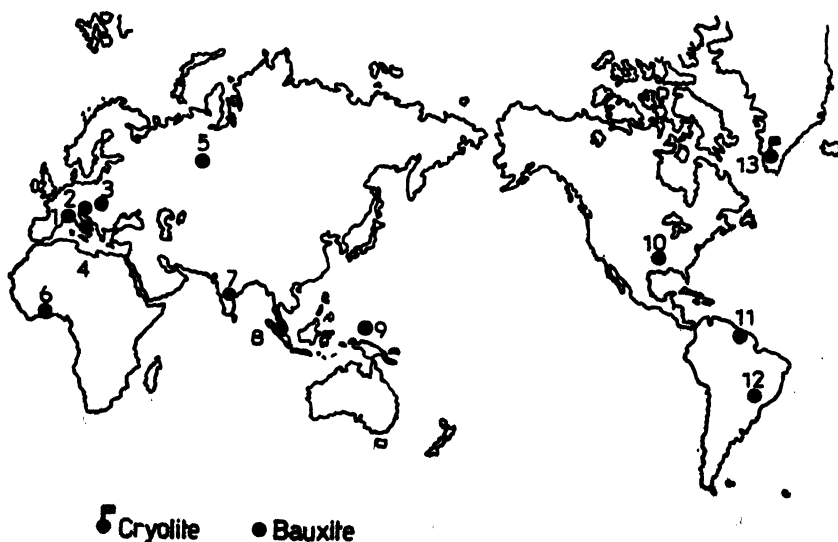


Fig. 13. The more important sources of bauxite and cryolite.



the temperate and torrid zones of the world. The purification of bauxite is today almost exclusively carried out by the Bayer process, in which, as shown in Fig. 14, bauxite<sup>1</sup> after roasting in rotary kilns<sup>2</sup> is ground to a fine powder in ball mills<sup>3</sup>. It is then charged into autoclaves or kiers<sup>4</sup> for the process of digestion in caustic soda liquor of 45° Beaumé at 165° C (329° F) under a steam pressure of 90 lbs per square inch and is converted into sodium aluminate which is dissolved, while the impurities remain out of solution. In the filter presses<sup>6</sup> the residue ("red mud")<sup>7</sup> is separated from the liquor, which is then transferred to the decomposers<sup>8</sup> and diluted several times for the precipitation of alumina hydrate to take place by hydrolysis. This hydrate is separated from the liquor in rotary drum filters<sup>9</sup>. The filtrate is reconcentrated to 45° Beaumé in evaporators<sup>12</sup> and is used again for another cycle of digestion, etc. The alumina hydrate<sup>10</sup> is calcined in rotary calciners<sup>11</sup> at about 1400° C. The pure alumina so obtained is dissolved in molten cryolite ( $\text{AlF}_3 \cdot 3\text{NaF}$ ) in the reduction furnaces or pots (Fig. 15). Direct current is led into the electrolytic bath at the carbon anodes C, which must be made of the purest carbon, and is led out of the bath through the bottom which is likewise made of pure carbon. Through the effect of the electric current, the oxygen of the alumina ( $\text{Al}_2\text{O}_3$ ) separates at the anode or positive pole and burns up the carbon to carbon dioxide and carbon monoxide, while the metal separates at the cathode or negative pole. The metal is tapped or taken out of the reduction furnace once every 48 hours. The usual purity of the aluminium produced by this process runs between 99.0% and 99.8%. Fig. 16 shows a modern furnace room, or pot room, with furnaces equipped with continuous Soderberg electrodes. In order to collect the evolved gases, the reduction furnaces in the illustration are of the completely enclosed type.

If still purer metal is required, this has to be produced by a further

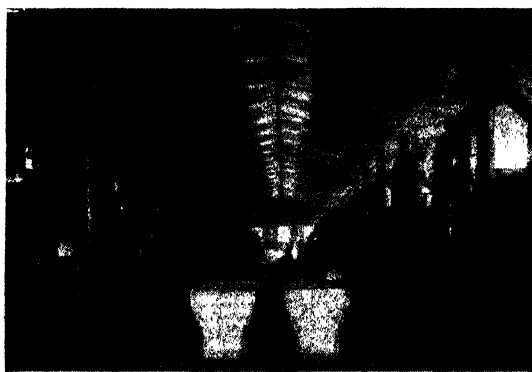


Fig. 16. Modern furnace room or potroom with 36 000 amp Soderberg furnaces.

special electrolytic refining process, which was first developed by an American, HOOPES. The starting material for this process as used by the Aluminium-Industrie-Aktien-Gesellschaft at Chip-pis is an alloy of aluminium with about 30% of copper, the "anode alloy", which lies on the bottom of the electrolytic refining furnace. Above that is the electrolyte composed of a mixture of

fluorides of barium, sodium, calcium and aluminium having a melting point of  $740^{\circ}\text{C}$ . The specifically lighter aluminium floats on top of the electrolyte, the system being known as the 3-layer system. By this process aluminium of 99.99% purity and over can be obtained, which possesses an extremely high chemical resistance.

### c. *Economic considerations*

One ton of aluminium requires 2 tons of alumina and this requires 4 tons of bauxite. For 2 tons of alumina, 95 million B. Th. U's are required for the various thermal processes, which needs about 8 tons of low grade coal. For the reduction of alumina to metallic aluminium approximately 20 000 kWh of electrical energy are consumed per ton of aluminium. For countries poor in coal but rich in water power it is clear that it is only the reduction of alumina by electrical energy that can be carried out economically, while the alumina production that is required in great volume to meet this, must be carried out in places where fuel is cheap. While bauxite contains on an average 60% of alumina, the most widespread ore in nature, clay, shows only 25 to 40% of alumina with a high percentage of silica. Thus, to produce one ton of alumina, about twice the weight of clay is needed compared with bauxite, and the cheap Bayer process is unsuited for dealing with raw materials high in silica. For these, other processes such as the PEDERSON have been invented, in which a mixture of iron ore, coke, lime and aluminous material, are converted to pig iron and a lime-alumina slag. From this slag alumina is extracted by a conventional method such as by the Bayer process. The clay process also requires a great quantity of heat. This also applies to the S T process developed by the Goldschmidt A.G., Essen, in which calcined clay is decomposed with sulphuric acid. From the sulphite of alumina solution so obtained, basic sulphite of alumina is precipitated on heating to about  $100^{\circ}\text{C}$  ( $212^{\circ}\text{F}$ ). The sulphuric acid is driven off by calcination, and is returned to the process, while the impure alumina left is further purified by the Bayer process. None of these processes can be carried out in countries short of coal, thus such countries are entirely dependent on the import of foreign alumina, and not on bauxite as is often incorrectly supposed.

In the early days the American, HALL, and more recently his fellow-countryman FRARY have devised processes for the electrothermic production of alumina, in which bauxite mixed with the required quantity of coke

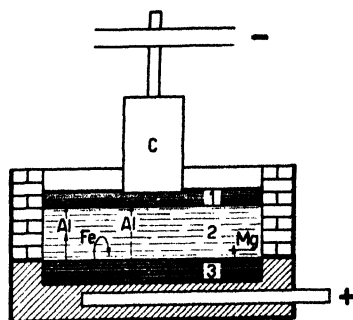


Fig. 17. Diagram of aluminium refining cell.

1 = Cathode metal; 2 = Electrolyte;  
3 = Anode alloy

is smelted in electric arc furnaces for the reduction of impurities, principally iron, silicon and titanium. From this is obtained ferrosilicon and an aluminous slag, which is granulated by dropping in water or blowing with steam. Another well-known process, invented by HAGLUND comes from Sweden. All these processes, however, have the disadvantage that an alumina is produced of insufficient purity for present day demands.

To illustrate the importance of aluminium production to the electric power industry, it serves to mention that in 1940, of a total generation of electrical energy in Switzerland of about 6 500 million kWh. Some 700 million kWh were used for the reduction of aluminium, and 35 million kWh for the semi-fabricating stages of processing the metal. Thus in total 11.3% of the entire generation of electrical energy in Switzerland was used for aluminium manufacture.

### 3. MAGNESIUM

#### a. Historical

Magnesium was first isolated by DAVY in 1808<sup>1</sup> by the electrochemical reduction of magnesia and cinnabar in naphtha using a mercury cathode. In 1828, BUSSY reduced magnesium chloride by heating with potassium, and in 1852 BUNSEN<sup>2</sup> was the first to produce magnesium by the electrolysis of molten magnesium chloride, a process widely used today. In 1857, SAINTE-CLAIRE DEVILLE improved BUSSY's method by the substitution of sodium for potassium, and he was the first with CARON to attempt to redistil magnesium in a current of hydrogen. The commercial development of magnesium production lagged far behind that of aluminium until G. PISTOR, a director of Griesheim Elektron, which was later merged in the chemical firm of I. G. Farben, was successful after great perseverance in commercially developing magnesium electrolysis and magnesium alloys at the beginning of this century. The magnesium alloy Elektron was first introduced to the public at the Frankfort Aeronautical Exhibition in 1909. According to PISTOR<sup>3</sup> himself large scale development was commenced in 1920. The considerable difficulties in the fabrication of magnesium alloys had the result that the production of magnesium was restricted to only about 10% of that of aluminium, and the I. G. Farben and their licensees in different countries had an assured monopoly up to the outbreak of World War II. Since then a big independent production has been developed in America, attaining a capacity of 240 000 tons per year.

The most important modern reduction process is the electrochemical

<sup>1</sup> Phil. Trans. Roy. Soc., London, Vol. 1 (1808) 333.

<sup>2</sup> Ann. Chem. Pharm., Vol. 82 (1852) 137.

<sup>3</sup> Zeitschrift für Elektrochemie, Vol. 42 (1936) 437.

one by the electrolysis of molten alkali chlorides, and in this the resulting chlorine gas is collected and used again in the process. During the war the thermal reduction of magnesium came into prominence, but this has now declined.

#### b. Production of magnesium

The principal raw material used in the electrochemical reduction process for magnesium is carnallite ( $\text{MgCl}_2 \cdot \text{KCl} \cdot 6\text{H}_2\text{O}$ ), but artificial magnesium chloride is also much used. Beside this there is the magnesium content of sea water which is 0.14% in the Atlantic and as much as 2.7% in the Dead Sea, from which the magnesia can be precipitated by milk of lime. For the thermic reduction process, magnesite,  $\text{MgCO}_3$ , with 29 % of magnesium, and dolomite,  $\text{MgCO}_3 \cdot \text{CaCO}_3$ , with 13 % of magnesium are chiefly used, the oxide being obtained from these by calcination.

In the electrolytic process, magnesium chloride is decomposed, being dissolved in a molten salt electrolyte composed of a mixture of alkali and alkaline earth chlorides having a melting point of about  $700^\circ \text{C}$  ( $1292^\circ \text{F}$ ). Owing to its low specific gravity, the metallic magnesium which separates at the cathode floats on the electrolyte and for this reason the chlorine generated at the anode must be prevented from recombining with the magnesium, as shown in Fig. 18. The chlorine is therefore collected in the bells surrounding the anodes and is led away for re-use in the production of fresh magnesium chloride. The voltage across the bath is about 6 volts and cells taking 10 000 to 30 000 amp are in use. In large modern units, the energy consumption is as low as 17 000 to 18 000 kWh per ton. The purity of the cathode magnesium is generally about 99.9%. The impurities mostly are Fe, Al, Si, Cu and Cl. If specially pure magnesium is required, a further purification can be effected by sublimation in vacuo, by which the content of individual impurities can be generally reduced to below 0.01%.

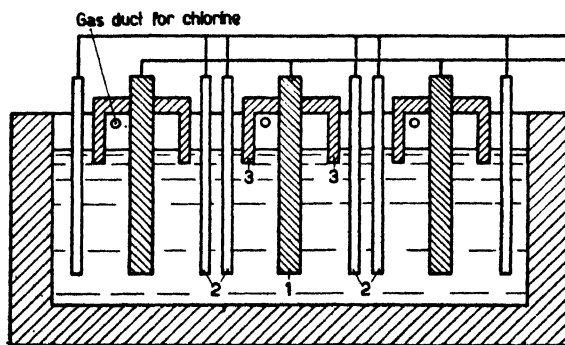
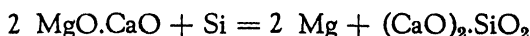


Fig. 18. Magnesium electrolytic cell.

1 = Anode 2 = Cathode 3 = Anode bell

In the thermic process, in preference to carbon, the reducing agents used are calcium carbide, ferrosilicon, and to a lesser extent aluminium scrap. When carbon is used as a reducing agent, carbon monoxide gas is evolved as well as magnesium vapour, which reoxidises on cooling, causing reduction by this method to be very difficult to effect. With the other reducing agents, however, a solid oxide is formed from which the magnesium vapour separates at the elevated temperature, so that there is no reoxidation in these cases. With calcined dolomite and silicon the reaction is:



This thermal reduction is generally carried out in a vacuum and the magnesium formed has to be subsequently remelted. Fig. 19 shows a vacuum reduction furnace for magnesium.

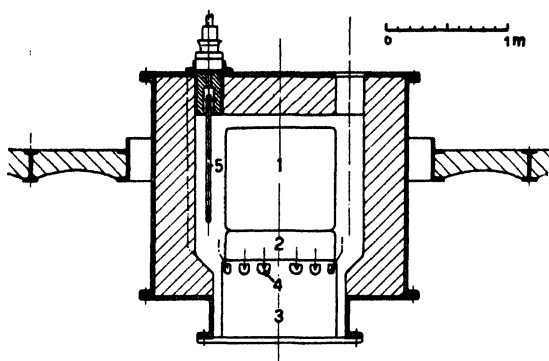


Fig. 19. Magnesium thermic reduction furnace.

1: Charge 2: Insulating stand 3: Condenser 4: Mg vapour 5: Heating element

### c. Economic considerations

In the electrochemical reduction of magnesium, about 20 000 kWh per ton are expended, about equal to aluminium, while in the thermic process, including the energy used for the prior production of ferrosilicon or calcium carbide, still greater amounts of energy are consumed. On the other hand, the thermic process requires no chemical treatment of the ore, so that the entire process is carried out by the electrothermic method. Owing to the difficulties of the alkali chloride electrolysis and the heavy power consumption of the thermic process, the market price of magnesium is appreciably higher than that of aluminium, even the price per unit volume allowing for its specific gravity of 1.8 being somewhat higher than for aluminium. The greater difficulty in working magnesium and its smaller corrosion resistance than aluminium as well as its lower modulus of elasticity of 2 650 tons ( $6 \times 10^6$  lb) per sq. in. against 4750 tons ( $10.5 \times 10^6$  lb) per sq. in. for aluminium are disadvantages which tend to restrict the use of magnesium, the lightest metal of commerce.

## CHAPTER II: ALLOYS

### 1. THEORY OF ALLOYS

#### a. *General*

Pure aluminium, like most pure metals, has good working and forming properties and a high resistance to corrosion, but low mechanical strength and poor machining properties with cutting tools. Hence it is used principally for utility articles for the household and industry, for instance in the chemical, and food manufacturing and distributing industries, and for low stressed constructional parts, also for wire, tape and busbars for electrical conductors. In addition, when rolled into foil less than one thousandth of an inch thick, it is used on a large scale as a packaging material for a variety of products in daily use, as a heat-insulating material against heat or cold, and for electrical condensers. It is also used for high voltage cables. The higher the purity of aluminium, the better are the corrosion resistance and working properties of the metal. Thus "Raffinal"<sup>1</sup> (refined or super purity aluminium), with a purity of over 99.99 %, possesses an outstandingly high reflecting power and so finds an extensive application for reflectors (Fig. 20). Super purity aluminium is used in the chemical industry on account of its incorrodibility. The electrical conductivity of super purity aluminium is over 38 m/Ohm.mm<sup>2</sup> (64% copper standard) as compared with 36 (60%) for 99.5% purity metal.

When other metals are added to aluminium, its strength and machining qualities are improved at the expense of its plastic workability and, in some cases, of its corrosion resistance. Silicon, copper, zinc and magnesium are alloyed with aluminium in substantial proportions, while iron, manganese, nickel, chromium, titanium, antimony, cadmium, cerium, lithium, beryllium and molybdenum are used in smaller proportions with various beneficial effects. Of these elements, magnesium and zinc are soluble in aluminium up to about 3% at room temperature, while the solubility of copper is about 0.5 % and the remaining metals are practically insoluble, but form intermetallic compounds and eutectics with aluminium. Titanium, tungsten, cerium and molybdenum are metals that have a strong

<sup>1</sup> Registered trade-mark



grain refining effect even in proportions of only 0.1%, while manganese confers a general improvement in corrosion resistance, and antimony does so against sea water. Cobalt and nickel have a favourable effect on

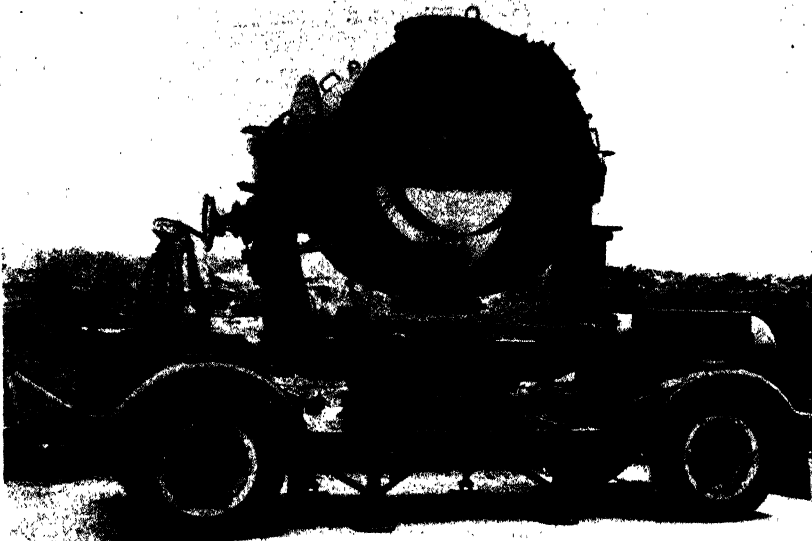


Fig. 20. Large searchlights of "Reflectal" (Color Metal, Zürich).

working properties and strength, while cadmium and tin confer an additional increase in hardness in the heat-treatable (age-hardening) alloys which are described later. Sodium is added in the manufacture of the aluminium-silicon eutectic alloy for the purpose of improved properties by modification. Bismuth, lead, cadmium, tin and magnesium help to cause the formation of short chips in the machining of the free-machining alloys. Magnesium in particular assists precipitation hardening.

#### b. *Precipitation hardening*

The phenomenon of precipitation hardening or age-hardening in aluminium alloys was first observed by WILM. Since then age-hardening effects have been discovered in other light and heavy metals, and this is now of much technical importance. For an explanation of precipitation hardening, we shall do best to consider the simplest case of the aluminium-copper alloys.

The constitutional diagram in Fig. 21 has a phase boundary line falling from the 548° C (1018° F) eutectic horizontal at 5.7 % copper, which shows a diminution of the solubility in copper in aluminium in the solid

state with falling temperature. At 548° C (1018° F) as much as 5.7% of copper is soluble in aluminium, but this solubility diminishes to less than 0.5% at room temperature. Conversely on heating the alloy, the solubility increases in accordance with the line in question to a maximum of 5.7%. This maximum solubility, however, is only reached after prolonged heating, and in ordinary industrial practice, we only count on a maximum solubility of 5% at the eutectic temperature. If such an aluminium-copper alloy, after a prolonged heating at 530° C\*, is rapidly cooled to room temperature by quenching in cold water, the copper then remains in solid solution in the condition of metastable equilibrium, as it is termed. This process is known as solution heat-treatment. If the kinetic energy of the molecules is sufficiently increased by raising the temperature to between 100° and 200° C, (212° to 392° F) a gradual precipitation of the copper from this unstable undercooled condition takes place, on which it separates from the solid solution in an incipient molecular dispersoid condition.

We must now consider the mechanism of this precipitation, which modern metallurgical knowledge has in recent years explained fairly completely, without, however, as yet having revealed the ultimate cause. We know that atoms of a single pure metal arrange themselves in a quite distinct geometrical manner on solidification. Thus aluminium solidifies

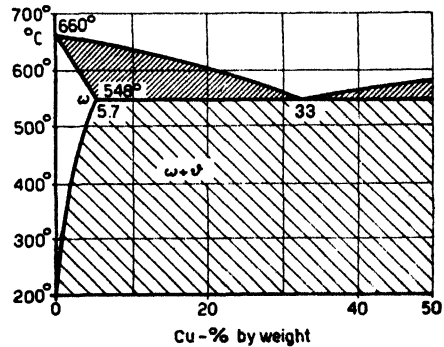


Fig. 21. Equilibrium diagram of the Al-Cu alloys.

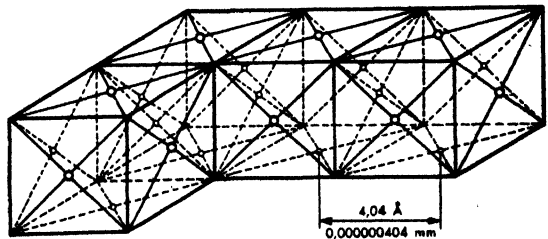


Fig. 22. Electron micrograph of aluminium crystals at 20 000 diameter's magnification, and space lattice.

with the face-centred cube arrangement (Fig. 22) with a cube edge length or parameter of 4.04 Å (0.000 000 404 mm). That the cubic crystal form

\* 986° F.

is never actually seen is due to the fact that in crystal growth from the melt, the full development of individual crystals is obstructed by the growth of adjacent crystals (Fig. 23). If a second metal, namely copper, in the case we are considering, is introduced in solid solution in aluminium, then copper

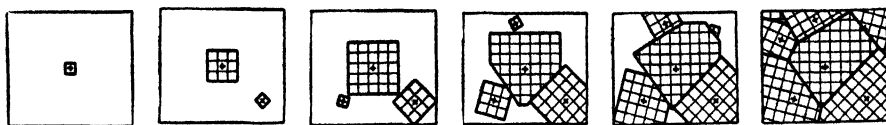


Fig. 23. Conception of formation of nuclei, and crystal growth from the molten metal. atoms enter the space lattice in place of some aluminium atoms (Fig. 24). Since at falling temperatures, the solubility of copper in aluminium progressively diminishes, then in precipitation hardening copper atoms must be precipitated from the supersaturated solid solution. In the first stage of precipitation all that takes place is an orientating of the copper atoms, and it is only on slow heating at over  $100^{\circ}\text{C}$  ( $212^{\circ}\text{F}$ ) that there takes place an actual separation of the copper from the aluminium crystal in a dispersed molecular form. Fig. 25, right, shows a rotating crystal X-ray photograph of an Al-Cu-Mg alloy quenched from  $525^{\circ}\text{C}$  ( $977^{\circ}\text{F}$ ) and aged for 15 hours at room temperature (i.e., "naturally" aged for 15 hours), while the left-hand portion of the illustration shows the same alloy similarly quenched but artificially age-hardened (or warm-aged) for 24 hours at  $150^{\circ}\text{C}$  ( $302^{\circ}\text{F}$ ). The picture does not depict the precipitate, but the ground-mass, the solid solution of copper in aluminium. With progressive precipi-

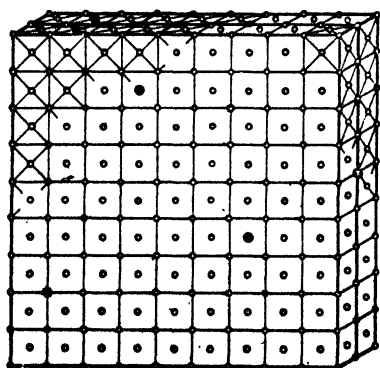


Fig. 24. Positions of Al and Cu atoms in the lattice.

● = Al  
○ = Cu

ation, the solid solution becomes low in copper. This leads to an enlargement of the lattice which shows up in the rotating crystal X ray photograph in a displacement of the reflection points, particularly marked in the inner reflection points with great angular deviation. The vertical distance between the four opposite inner reflection pairs is smaller in the left-hand picture than in the right-hand. Similarly, the horizontal distance is greater since displacement takes place on a fixed circle. If the heating is carried further still, these precipi-

tates agglomerate into large dispersed particles by a process of coalescence.

In the first and second stages of the rejection process, very considerable

stresses arise in the lattice, which manifest themselves in an increase in hardness and strength, without loss of elongation. When on the other hand hardening is brought about by cold work, it is in this case accompanied



Fig. 25. Rotating crystal  $X_{ray}$  photograph showing the precipitation of Cu from an Al-Cu-Mg-alloy (Göer and Sachs).

by a marked decrease in elongation. Fig. 26 shows graphically the effects of both cold working and age-hardening which latter in ordinary commercial alloys must be stopped short at the appropriate stage to avoid re-softening. If coalescence of the precipitates occurs in consequence of further heating, the inter-atomic stresses again disappear and an appreciable softening of the alloy takes place. For all age-hardenable alloys the important rule is, that a subsequent heating of the alloy to over  $100^{\circ}$  to  $150^{\circ}$  C ( $212^{\circ}$  to  $302^{\circ}$  F) according to the particular alloy in question reverses the age-hardening effect and causes a loss of strength in the alloy. Age-hardening is thus of no advantage in any application where the material is to be in use for lengthy periods at temperatures of over  $100^{\circ}$  C ( $212^{\circ}$  F). Inter-

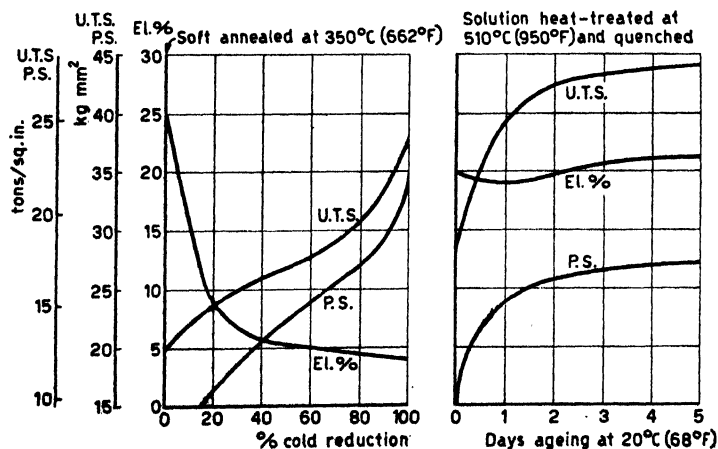


Fig. 26. Effect of cold work and precipitation hardening on the mechanical properties of Avional (Duralumin) (Al-Cu-Mg).

atomic stresses of another kind, due to distortions of the space lattice arise also in the cold working of aluminium but in this case the increase in strength is accompanied by a decrease in elongation (Fig. 27). In this case also, on subsequent heating the stresses due to the distortion of the

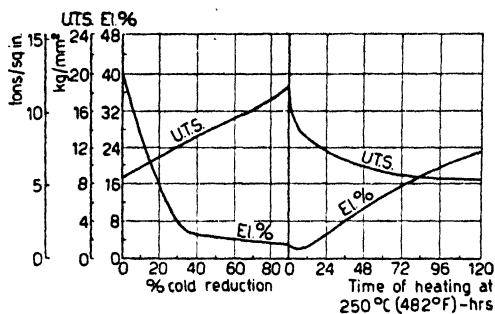


Fig. 27. Effect of cold work and heating on pure aluminium.

space lattice are reduced because of a so-called crystal recovery or stress-relief, with consequent decrease in strength and increase in elongation.

That atoms can in actual fact migrate in the solid state from one crystal to another by diffusion is shown by the following experiment:

Into a block of an aluminium alloy containing 5% Mn, so that there was intimate contact between the two alloys. Fig. 28, left, shows a section of the contact surface of the two alloys at a magnification of 60 diameters. After a 7-day heating at 550° C (1022° F) the change in the structure can be

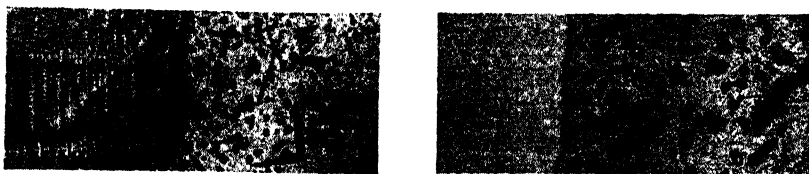


Fig. 28. Diffusion of silicon and manganese on 7-day heating and 550°C (1022°F).

clearly seen in the right-hand picture, where the migration of silicon into the manganese alloy and the formation of a new phase (manganese silicide) is to be seen.

### c. Binary alloys

The most important binary alloys are those with copper, magnesium or silicon. The equilibrium diagram of the aluminium-copper alloys, as far as it is of interest to the aluminium industry, is reproduced in Fig. 21. As a hardener alloy for the production of the ordinary commercial aluminium-copper alloys, some works use either a 50% or 54% alloy, the latter corresponding to the compound  $\text{Cu Al}_2$ , while others use the eutectic

33% alloy, which of course has the lowest melting point, this being  $548^{\circ}\text{C}$  ( $1018^{\circ}\text{F}$ ) as compared with  $590^{\circ}\text{C}$  ( $1094^{\circ}\text{F}$ ) for the 54% alloy.

An eutectic alloy is one the constituents of which are mutually insoluble but which solidify at the same temperature in a state of extremely fine subdivision side by side. Due to this habit, such an alloy has a sharply defined freezing point, in contrast to the other alloys of the series, and shows a very fine grained primary structure which is accompanied by high mechanical properties. Fig. 29 illustrates the structure of the Al-Cu eutectic.



Fig. 29. Al-Cu eutectic.

The most important of the binary eutectic casting alloys is the aluminium-silicon alloy, called *Alpax*<sup>1</sup> by its inventor A. Pacz in 1920, and in European countries known as *Silumin*<sup>1</sup> or *Silafont*<sup>1</sup>. If this alloy is cast without a certain special treatment, the resulting structure is coarse as illustrated in Fig. 30, left, showing large plate-like silicon crystallites, in which condition the alloy has inferior mechanical properties and is no better than

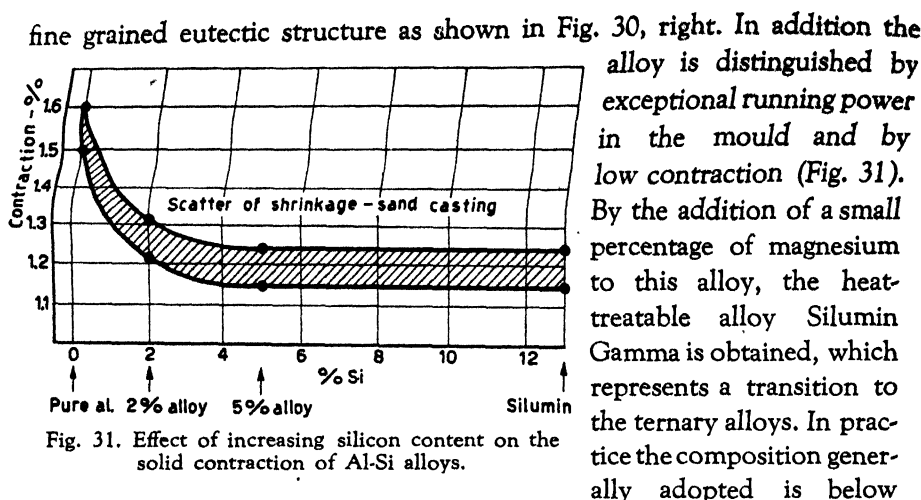


Fig. 30. Eutectic Al-Si alloy "Silumin".

Left — not modified.  
Centre — hypo-eutectic, modified.  
Right — 14% Si eutectic, modified.  
("Alpax" and "Silumin" are trade-marks).

ordinary cast iron. Pacz discovered that an addition of 0.1% of sodium to the molten alloy a few minutes before casting resulted in an extremely

<sup>1</sup> Registered trade-mark



the exact eutectic. In the hypo-eutectic alloys the excess of aluminium forms white dendritic islets in the silicon eutectic (Fig. 30, centre).

In recent years the aluminium-magnesium alloys with magnesium contents up to 12% have again come into prominence. As early as 1899 these were discovered by MACH and with great expectations were put on the market under the trade name Magnalium. Owing to an insufficient degree of purity in the alloying constituents used therein, especially the magnesium, their corrosion resistance was found to be insufficient for general commercial use and the Magnalium alloys lapsed into oblivion until the advances in the production of pure magnesium permitted the development of aluminium-magnesium alloys of high corrosion resistance. These are employed both as casting and as wrought alloys. In general, however further constituents are added, and we shall deal below with the resulting complex alloys.

#### d. Complex alloys

Complex alloys are employed in industry to a considerably greater extent than binary alloys. In general complex alloys have a preponderating addition of 2 to 15% of one principal alloying constituent, with minor additions of under 2% of other metals. Certain metals form chemical (intermetallic) compounds with one another, the most important being  $\text{Cu Al}_2$ ,  $\text{Mg}_2\text{Si}$ , and  $\text{Mg Zn}_2$ . Alloys of aluminium with these compounds form a borderline class between binary and complex alloys, and are termed quasibinary alloys. As with other chemical substances, the formation of compounds often gives rise to alloys with entirely different properties from the individual metals. Thus for example even a small proportion of zinc in the absence of magnesium perceptibly impairs the corrosion

resistance of aluminium alloys, while in contrast to this the addition of small proportions of Mg Zn<sub>2</sub> give alloys of very good corrosion resistance particularly against seawater. For this, these alloys must without fail be homogenized by heat-treatment.

The Al-Mg-Zn alloys have recently acquired some importance particularly for sheets and sections, with a Mg content 2.5 to 3.5% and Zn 4.5 to 5%. These alloys have an undesirable characteristic that after heating at low temperatures they are susceptible to stress-corrosion. Further additions and special heat-treatment help to overcome this.

Another important alloy is one with the additions of 0.5% Mg and 1% Si (See also pp. 33, 36).

The most important complex alloy is the Al-Cu-Mg-Mn-Si alloy invented by WILM in 1906 and patented in 1909. This alloy with its particular composition of 2 to 5% Cu, and Mg, Mn and Si contents ranging from 0.3 to 2% is a special case of the heat-treatable alloys, as it age-hardens even at room temperature to maximum strength without suffering any subsequent diminution of strength at this temperature. At 20° C (68° F) the period for completion of age-hardening is about 4 days. With higher temperature, the age-hardening is correspondingly more rapid (Fig. 32), and with lower temperature is slower, while at about -20° C (-4° F) only a slight amount of age-hardening effect takes place.

This spontaneous or natural age-hardening has the advantage that a subsequent artificial warm-ageing at elevated temperature is not needed and there is no risk of passing the hardness maximum, but there is also a disadvantage that the alloy cannot be heat-treated to different degrees of hardness as with the warm-ageing alloys, and also cannot be further age-hardened after further cold working at any desired time later. This alloy is known as Duralumin<sup>1</sup> in many countries, while in Switzerland it is chiefly known as Avional<sup>1</sup>.

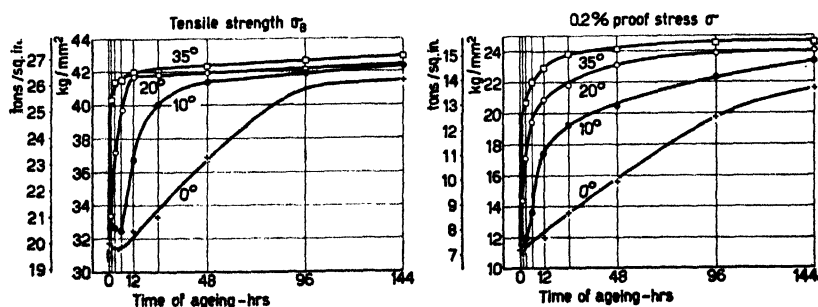


Fig. 32. Curves of age-hardening for Avional. (Duralumin) Al-Cu-Mg, wire at different temperatures in °C.

<sup>1</sup> Registered trade-mark



Since a warm-ageing alloy offers many advantages for fabricating purposes, an Al-Mg-Si-Mn alloy with 1% Si and about 0.6% Mg and Mn has been developed. The warm-ageing of this alloy, which is known by the name of Anticorodal<sup>1</sup>, is carried out at 130° to 160° C (266° to 320° F). With a 6 to

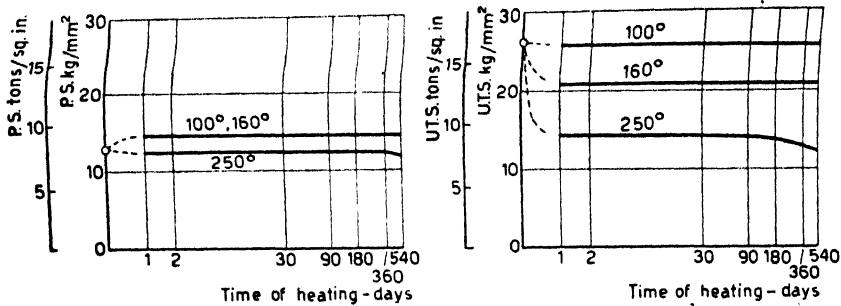


Fig. 33. Effect of time of heating at 100, 160 and 250°C (212, 320 and 482°F) on the proof stress and tensile strength of Peraluman 2 (Al-Mg-Mn) extruded sections tested at the same temperatures).

8-hour artificial or warm-ageing at 130° C (266° F), the semi-hard quality is obtained, and the fully hard quality with the same time at 160° C (320° F).

A heat-treatable alloy with an outstandingly high strength at elevated temperatures is Y alloy developed by ROSENHAIN in England, containing 4% Cu, 2% Ni, 0.5% to 1.5% Mg, and this is used particularly for motor pistons and cylinder heads. There is also a whole series of different heat-treatable alloys with a basis of Al-Cu-Ni-Mg-Si-Fe-Ti also developed in England by Rolls Royce and High Duty Alloys under the name RR alloys<sup>1</sup>, and these belong in general to the Y-alloy or Duralumin group.

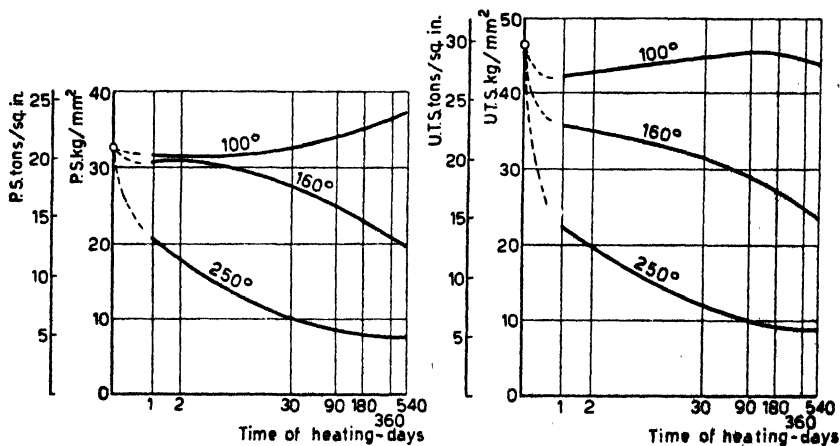


Fig. 34. Effect of time of heating at 100, 160 and 250°C (212, 320 and 482°F) on the proof stress and tensile strength of Avional (Duralumin) (Al-Cu-Mg) extruded sections at the same temperatures.

<sup>1</sup> Registered trade-mark

Of the non-heat-treatable alloys those with magnesium content of 2% to 10% and small manganese contents are of importance. Since these do not age-harden and their strength depends entirely on their magnesium content, they are of special interest for welded work. One drawback is

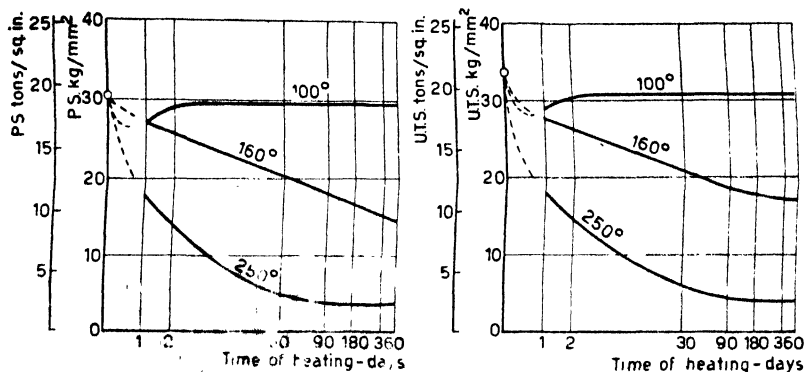


Fig. 35. Effect of time of heating at 100, 160 and 250°C (212, 320 and 482°F) on the proof stress and tensile strength of Anticorodal (Al-Mg-Si alloy) extruded sections tested at the same temperatures.

the difficulty of rolling the higher magnesium contents of over 5% and the tendency to intercrystalline corrosion in the "let-down" condition, which renders a special heat-treatment necessary.

Figs. 33 to 35 show graphically the effects of long-time heating on the tensile properties of some heat-treatable and some non-heat-treatable complex alloys. These graphs show clearly that all those alloys which are increased in strength by heat-treatment or cold work undergo a marked diminution in strength with prolonged heating at over 100° C, and thus precipitation hardening is not generally of benefit for application under such conditions.

Furthermore, it must be mentioned that although with copper containing alloys the corrosion resistance is very considerably improved by heat treatment, as the warm-ageing of the Al-Cu-Mg alloys brings a certain reduction in corrosion resistance due to a change in the electrochemical solution potential (Fig. 36), it is advantageous that artificially aged alloys of this type are clad for general purposes.

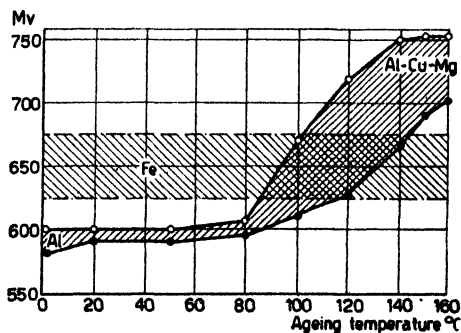


Fig. 36. Effect of warm ageing on the electrochemical solution potential of Avional (Duralumin) compared with that of mild steel.

The increased strength conferred by precipitation hardening can of course be still further increased by cold working. With this as shown in Fig. 37, there is the greatest gain of strength if the cold working is carried out after the completion of age-hardening. If the cold work is applied immediately after quenching, it causes a considerable acceleration of any subsequent precipitation hardening, but on the other hand a lower strength is finally obtained in this way than by cold working after age-hardening has been completed.

In conclusion we should mention the aluminium-zinc-copper alloy, often called the German alloy, which is not of much importance today. This casting alloy was used in considerable quantities in Europe especially for automobile castings in the early days of the motor industry, while in America the binary aluminium-copper alloy, sometimes called the American alloy, was preferred.

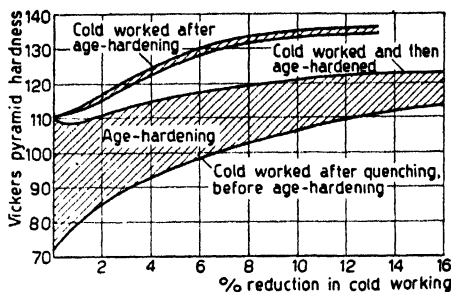


Fig. 37. Effect of cold work before or after ageing on the tensile strength of Avional (Al-Cu-Mg) (Duralumin).

## 2. COMMERCIAL LIGHT ALLOYS

In their commercial applications, aluminium alloys are divided into two main groups, casting alloys and wrought alloys, the latter being those alloys shaped by plastic deformation under pressure by rolling, extruding, forging, stamping, pressing or drawing. In each group we have to distinguish between common and heat-treatable alloys. Since aluminium can be alloyed with a great number of other metals it is not surprising that in the course of time the number of alloys which were put on the market increased tremendously, some of these being rationally developed, but a greater number of them not so. In another place<sup>1</sup> the author has published a compilation of all alloys in use at the time, as far as could be ascertained, to the number of 402, in which in many cases similar compositions went under several different names. The general trend towards standardization has extended in most countries to include the light alloys, and a list of alloys in general use and the properties of the same reveals a strong similarity between the standard specifications of various countries. In the ensuing pages the designations used for the various alloys are those of the VSM<sup>2</sup> specifications.

<sup>1</sup> A. v. ZEERLEDER, *Technologie des Aluminiums und seiner Leichtlegierungen*, 4th Edition, pp. 49-80, Akademische Verlagsgesellschaft, Leipzig 1943.

<sup>2</sup> VEREIN SCHWEIZERISCHER MASCHINEN-INDUSTRIELLER (Swiss Machinery Manufacturers' Association)

In Table 3, standard alloys and their trade names in different countries are tabulated alongside one another. In subsequent pages, for the sake of simplicity, Swiss trade names are generally used with the VSM alloy designations.

TABLE 3  
TRADE NAMES OF STANDARD ALUMINIUM ALLOYS IN VARIOUS COUNTRIES \*

WROUGHT ALLOYS

Alloy	Switzerland	England	U.S.A.	France	Italy	Germany
Al-Mn	Aluman 3S M115	BA60 NA 3S DTD 213A	3S SAE29	Manganal	Aluman Resistal	Aluman Donal Finoman Heddal Mangel Osmagal Silal K
Al-Mg	Peraluman Type	BA 21 D7 RR66 DTD634		Alumag Duralinox Scléral	Peraluman Idronalio Itallumag	Hydronalium BSS BS-Seewasser F & G5 ML5
Al-1Mg	Peraluman 1 4S		4S SAE20		Peraluman 1	
Al-3Mg	Aludur 100 Peraluman 3 57S	BA27 Birmabright DTD180B	52S	Alumag 35 Duralinox H3	Peraluman 3	Hydronalium 3
Al-5Mg	Aludur 300 Peraluman 5 Aludur 500	BA28 MG5 BS AW6A	56S	Alumag 50 Duralinox H5	Peraluman 5	BS-Seewasser 63/05 MWU5

\* Most of the alloy names are protected as registered trade-marks.

TABLE 3. (Continued).

Alloy	Switzerland	England	U.S.A.	France	Italy	Germany
Al-7Mg	Peraluman 7	MG7 DTD 182A		Alumag 65 Duralinox H7	Peraluman 7	Heddenal 7 Hydronalium 7
Al-Si-Mg	Anticorodal 51S Korrofestal Aludur 531	BA24 BA25 DTD443	A51S 53S 61S	Vival Almasilium Inoxalium Impérium	Anticorodal Inalteral	BS-Seewasser 63/07  Anticorodal Legal II Deltal Pantal Duralumin K Qualität M Erge 4 Simagal 200 Ulmal Finodal Hathal C Howal RS Korrofestal Aludur 533
Al-Mg-Si	Aldrey Aludur 513	Silmalec BA301 BA352 BA353 BA35		Almélec Aldrey	Aldrey	
Al-Cu-Mg	Avional 17S 24S Aludur 570	Duralumin NA22S NA24S RR72 Du Brand Hiduminium DU DTD 390 DTD610A BSS477 BSS1080	17S 14S 24S	Alferium Carbium Duralumin	Avional Duralumin Superavional	Avional Alkumag 300 Aludur 570  Heddur Hodur Igedur

TABLE 3. (Continued)

Alloy	Switzerland	England	U.S.A.	France	Italy	Germany
Al-Cu-Mg (cont.)		6L1 5L3 2L38 DTD390	SAE24 SAE26	Duralcolum Fortal		Aludur 580 Aludur 630 Bergal A Bondur Deltumin Duralumin Finodur Hathal A  Rheindur Qualität Q Ulmium DM31 F & G1 ML1 MWU1
Al-Cu-Ni	Y-Legierung	Y Alloy 4L25 BSS478	18S ASTM-H	Alliage Y	Y-Alloy	Y-Legierung Duralumin W

CASTING ALLOYS — (PREFIX C FOR CASTING)						
C: Al-Mg	Peraluman type	Birmabright NA330	218 220 B61	G7 Duralinox	Peraluman	Niral Usonalium
C: Al-3Mg	Peraluman 3		214 SAE320 A214			
C: Al-5Mg	Peraluman 5	DTD 165		VB5		Hydonalium 5 BSS5
C: Al-10Mg		BA29 DTD300A BA45	214			
C: Al-Si			43 85 380 A108			

TABLE 3. (Continued)

Alloy	Switzerland	England	U.S.A.	France	Italy	Germany
C: Al-12Si	Silafont 1	L33 BA40 Wilnil Birmasil MVC BSS702	47 13 B32 ASTM-K SAE37	Alpa * C502	Italsil Silicalfa L3	Silumin
C: Al-12 Si-Cu	Kupfersilumin	BA42	A132			Kupfersilumin
C: Al-Si-Mg	Anticorodal	BA23	356 360		Anticorodal	Anticorodal
C: Al-2Si-Mg	Anticorodal 2.5Si					L 15 I
C: Al-5Si-Mg	Anticorodal 5Si	DTD272	355 A355	41SM 26G		Pantal 5
C: Al-10Si- Co-Mg	Cobalt-Silumin 26G					Cobalt-Silumin
C: Al-12Si-Mg	Silafont-2	BA41 Wilnil 17	A132		Silumin-Gamma	Silumin-Gamma
C: Al-Cu-Ti	Alufont 3 Alufont 4	BA32 BA34 L11 BSS361 BSS362 DTD298 Y alloy BA33 BSS 704	108 112 113 122 195 212 142	AP33 W 41		
C: Al-Cu-Ni						

### a. Casting alloys

In the manufacture of castings, among other properties of the alloys used, their casting properties are of paramount importance. These comprise firstly fluidity, or power of running in the mould, then contraction and the solidification range of the alloy. The difficulties of accurately determining contraction are if anything exceeded by those in the determination of fluidity. COURTNY utilized a spiral chill mould, in which the alloy under test flowed for a certain distance before solidification caused the flow to stop, the length of the resulting spiral being taken as a measure of the

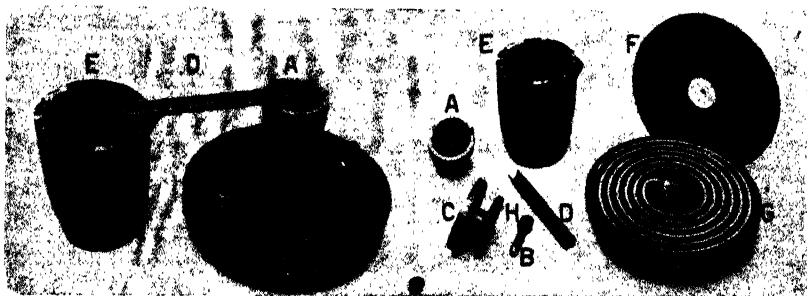


Fig. 38. Spiral chill mould for fluidity test (Courtney).

fluidity or running power of the alloy under test. Fig. 38 shows a method of testing in which the metal under test is cast at a predetermined temperature from an accurately controlled height into a spiral cast iron chill mould itself preheated to a predetermined temperature. The length of spiral run gives a measure of the fluidity.

As shown in Table 4, the tensile properties of the various casting alloys cover a wide range. We have alloys with a proof stress as low as 2.5 tons per sq.inch (5 500 lb./sq.in.) or as high as 18, (40 000) while the tensile strength ranges from 6 to 25 tons per sq. inch (13 000 to 56 000 lb./sq.in.). The degree of importance of tensile strength depends on the

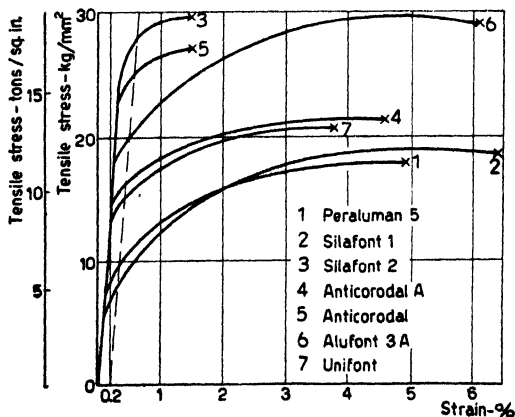


Fig. 39. Stress-strain diagram of different casting alloys.



application of the alloys and in parts which must withstand shock or fluctuating loads, the impact strength, fatigue (or endurance) strength and elongation count for more than tensile strength. Fig. 39 gives stress-strain curves typical of different aluminium alloys and shows that

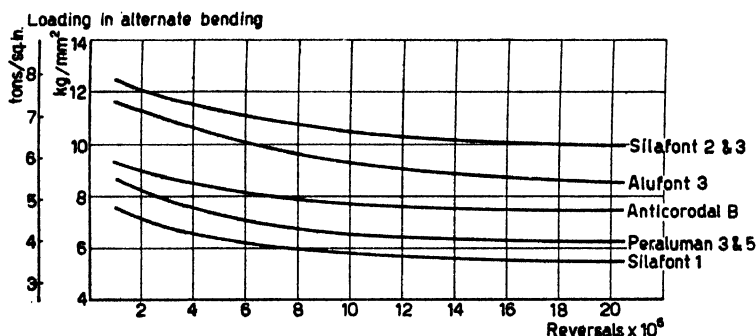


Fig. 40. Wöhler endurance curves of Al sand casting alloys.

with equal tensile strength Silumin Gamma (C: Al-12 Si-Mg) has a proof stress of 18 tons per sq.inch (40 000 lb./sq.in.), Alufont 3 (C: Al-Cu-Ti) on the other hand only 13 tons (29 000 lb.), while the latter has an elongation of 10% compared with 2½% for Silumin and Anticorodal B (C: Al-2Si-Mg). For statically loaded castings, Alufont 3 (called AP 33 by ALADAR PACZ) with its greater ease of manufacture, has the advantage. In the warm-ageing C: Al-2Si-Mg alloy (Anticorodal) the possibility of age-hardening to various degrees is an attractive feature.

In the case of moving parts, resistance to fatigue requires consideration as well as the static properties, so the fatigue strength becomes of increased importance the higher the fluctuating stresses in the part.

To obtain a correct picture of the fatigue strength (or endurance strength) under alternating load, the entire endurance curve, as shown in Fig. 40, 1-5, must be considered, as a reliable picture of the safe fatigue strength cannot be obtained from the appraisal of a single endurance test, especially, as is frequently the case, where the number of reversals is not stated. In general, casting alloys are tested to 20 million reversals of stress and wrought alloys to 100 million (see also p. 69).

#### b. Secondary alloys

A number of secondary casting alloys have been developed for use in the manufacture of castings where strength is not of prime importance.

The composition of these is governed principally by the kind of scrap available and therefore depends on the scrap market situation at the time, so that standard specifications may not always be practicable. In Table 5 are tabulated some current Swiss and British secondary casting alloys, with compositions and mechanical properties. Table 5a gives particulars of a type of wrought secondary alloy in present use in Britain. The corrosion resistance of secondary alloys would hardly be so good as that of the corresponding standard alloys of similar nominal composition owing to unavoidable impurities. Nevertheless, their lower price assures them of a steady market<sup>1</sup>.

### c. Wrought alloys

In the field of commercial wrought alloys, there is one binary alloy of note, Al-Mn (Aluman, BA6C, 3S) having an alloy content of 1 to 2% of manganese, which confers a somewhat higher strength than pure aluminium without loss of working properties or chemical resistance. This alloy is largely used for panels and casings in vehicle body and machine construction as well as in the cooking utensil industry. The eutectic Al-Si alloy (Alpax, Silafont, Silumin) which has been occasionally used for these purposes is now practically extinct as a rolling alloy.

With the Mg-Al alloys (Peraluman BA21, BA27, 52S, 56S, etc.) we find five groups with magnesium content increasing from 1 to 7%, to which a small manganese content is generally added, thus making virtually ternary alloys. The alloys are readily workable up to 5% Mg, and in the soft and half hard condition are very suitable for panel work, forming and welding. With Mg contents in excess of 5%, greater difficulties are encountered in working, due to the effect of the hexagonal structure of Mg, while owing to the solubility of Mg in Al being exceeded, the alloys become susceptible to stress corrosion, which calls for a special heterogenizing anneal. As this susceptibility is increased by subsequent heating, some care is called for in the working of this alloy. As Mg contents in excess of 5% confer only a small addition of strength, the higher alloys are of only minor interest.

Among the heat-treatable alloys, the Al-Si-Mg alloy Anticorodal (BA24, BA25, 51S, 53S, etc.) has found increasing application for general machine and vehicle construction. Due to the warm-ageing characteristic, this alloy can be supplied in different grades of hardness, and in the semi-aged condition is especially suitable for further mechanical forming, as with subsequent low-temperature heating to 160° C (320° F) after forming, the complete age-hardness can be generated. When completely copper-free,

<sup>1</sup> Scrap supplies, p. 113.

TABLE 5  
SECONDARY CASTING ALLOYS  
(SC = secondary casting)

Alloy Designation and Type	Application	Composition % Main elements				PHYSICAL PROPERTIES								
		Cu	Si	Mg	Fe	Con- dition *	Proof Stress		Tensile Strength		Elong- ation	Brinell Hard- ness	Spec. Grav.	Casting Contraction %
							Tons/ sq. in.	1000lb./ sq. in.	Tons/ sq. in.	1000lb./ sq. in.				
Swiss Alloys	Pressure die castings	2-4	2-5	-0.5	-1.5	As cast	7-10	16-22	11-14	24-31	1-3	65-85	2.8	1.15-1.25
		2-4	2-3	0.3-0.5	-0.8	As cast HT	8-11	18-24	9-14	20-31	0.5-2	60-80	2.5	1.15-1.25
UG3 (SC: Al-Cu)	Gravity die castings	4-10	-1	-0.2	-0.8	As cast	6-10	13-22	9-13	20-29	1-3	65-90	2.8	1.20-1.30
UG4 (SC: Al-Si-Mg)	General sand and die castings	-0.3	2-6	0.5-1.5	-0.8	As cast HT	6-10	13-22	8-13	18-29	1-4	50-70	2.7	1.30-1.40
UG5 (SC: Al-12Si)	General sand and die castings	-2	10-13	-0.2	-0.8	As cast	4-6	9-13	9-16	20-36	1-4	50-80	2.7	1.10-1.20
Some British Alloys DTD 424	Sand and die castings	2.5	5.5	(Mn 0.5)	{ Sand cast Die cast	{ cast	5.5	12	10	22	2.5	65		
		5.5	12	10.5			23	2.5	70					

DTD 428	Sand and die castings	7.5	3.5	(Zn 2.25)	Sand cast	5.5	12	8.5	19	—	73
					Die cast	7.0	16	11	24	1	80
LAC 112A	Sand and die castings	1—2	10	(Zn 0.9)	Sand cast	4.8—	11—	9.5—	21—	1	70
					Die cast	5.3	12	11.3	25	1	78
LAC 10	Sand and die castings	10		0.25	Sand cast	6	13	8	18		75
					Sand cast	9	20	12	27	1	85
					Die cast	11.3	25	14	31		120
					Sand HT	13.5	30	15	40		143
					Die HT						

\* HT = head-treated

TABLE 5a  
WROUGHT SECONDARY ALLOYS (BRITISH)

Alloy Type and Designation	Application	Average Composition %				Condition	MINIMUM MECHANICAL PROPERTIES					Specific Gravity approx.	
							0.1% P <sub>0.01</sub> Stress		Tensile Strength		Elongation in 2-in. %		Bend Test
		Cu	Mg	Mn	Si		Tons./sq. in.	1000 lb./sq. in.	Tons./sq. in.	1000 lb./sq. in.			
Al-Cu-Mg type Designation CGA* or DTD 479	{ Sheets and strip as used for the aluminium house (Gt. Britain)	3.6	0.63	0.5	< 0.65	Head-treated	12	27	22	49	8	3T**	2.8
		Clad with 5% of 99% al. on each side				Annealed	—	—	11	24	—	T	
	{ Extruded struct.-Class 1 ural sections as Class 2 used for the Class 3 alumin. house (Gt. Britain)	2.75	0.45	0.4	1.0	Heat-treated	14	31	22	49	8		
		2.75	0.45	0.4	0.6	Heat-treated	9	20	17	38	12		
						As extruded	—	—	11	24	12		

\* Commercial Grade Alloy (Great Britain).

\*\* T = Thickness of sheet.  
Other wrought secondary alloys would have mechanical properties resembling the virgin alloys given in Table 4.

the alloy displays high corrosion resistance and is well adapted to application in chemical plant and marine construction. Its corrosion resistance will be a maximum if it has a base of Raffinal or super purity aluminium. A copper content of 0.1% appreciably affects the corrosion resistance of this alloy.

The Al-Mg-Si alloy Aldrey is a variety of this type of alloy that contains no manganese and is particularly used for electric cables owing to its good electrical conductivity combined with high mechanical strength compared with pure aluminium wire. Solution heat-treatment and quenching are always applied to the rolled or extruded wire-rod of about 0.6 inch diameter, and this is followed by cold drawing in excess of 90% reduction without warm-ageing, which confers a high strength to the wire. A "letting-down" or stress relief by an 8 hour low-temperature anneal at 150° C (320° F) results in a sacrifice of a portion of the strength through crystal recovery, with which the material gains considerably in elongation, toughness and conductivity and is very suitable for conductor material (Fig. 41).

The Al-Cu-Mg alloy Duralumin<sup>1</sup>, 17S, or Avional<sup>1</sup> is employed in preference to all others in aircraft construction and in all other applications where maximum mechanical strength and high toughness are required. Since this alloy has a somewhat lower corrosion resistance than the Al-Si-Mg alloy Anticorodal, it is generally covered with a thin corrosion resistant layer by cladding it with pure aluminium or with Al-Si-Mg alloy. In general it is sufficient if the cladding is 5 to 10% of the total thickness. In order to increase the proof stress and tensile strength, the Al-Cu-Mg alloy which age-hardens naturally at room temperature is also sometimes warm-hardened. With this process the corrosion resistance of the alloy is impaired (see Fig. 36), so that it is important in such a case for the alloy

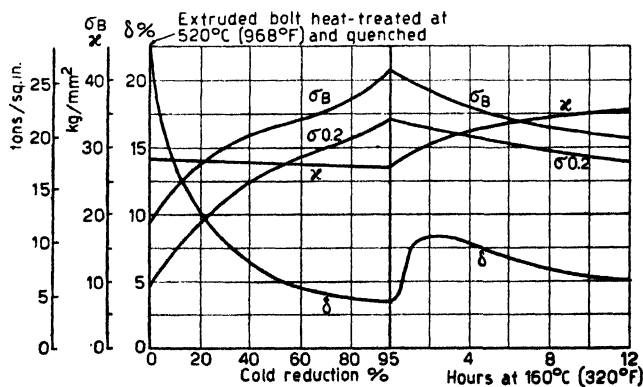


Fig. 41. Effect of cold work and letting down on tensile properties of Aldrey.

$\sigma_B$  = Tensile strength;  $\sigma_{0.2}$  = 0.2 % Proof stress;

$\delta$  = Elongation;

$x$  = conductivity m/Ohm. mm<sup>2</sup>

to be clad with pure aluminium or a corrosion resistant alloy. Details are given in Table 5a of a secondary alloy of this type.

The heat-treatable Al-Cu-Ni alloy which may be cast or forged is specially suited to high temperature applications such as motor pistons and cylinder heads. This

<sup>1</sup> Registered Trade-mark

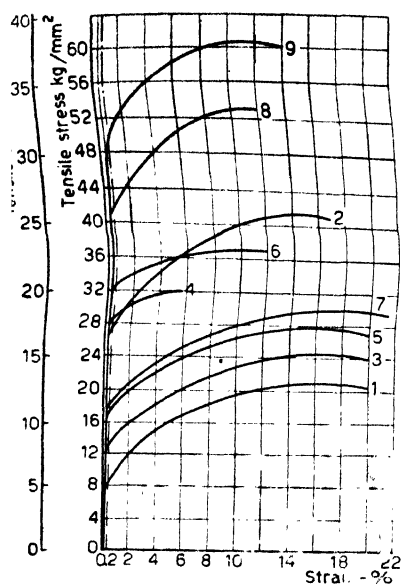


Fig. 41a. Stress-strain diagram of some wrought aluminium alloys.

- 1 Avional D soft.
- 2 Avional D heat-treated.
- 3 Peraluman-3 extruded.
- 4 Peraluman-3 hard.
- 5 Anticorodal A heat-treated semi-hard.
- 6 Anticorodal B, fully heat-treated.
- 7 Peraluman-5 extruded.
- 8 Avional-S clad, fully heat-treated.
- 9 Perunal.

alloy was called Y alloy by its originator, Dr. W. ROSENHAIN. The Al-Mg,Zn alloys<sup>1</sup> have the highest strength of all. To prevent stress corrosion in this type of alloy, other additions such as Cu, Ni, Mn, V or Cr must be included, and a special heat-treatment must be applied. In Table 6 are tabulated the compositions and mechanical properties of a few alloys of this type.

Fig. 41a shows stress-strain curves for various light alloys. The pronounced yield point above the proof stress characteristic of steel does not occur with these alloys. Different ratios of proof stress to tensile strength can be noted for the artificially (warm) aged and naturally (room temperature) aged alloys.

#### d. Magnesium alloys

The number of magnesium alloys on the market is much smaller than aluminium owing to the limited number of producers.

The alloys of technical value can be classified in four groups, namely :

1. Binary alloys: The principal example is the 2-11% Al alloy which, as shown in Fig. 42, is heat-treatable to give an increase in hardness up to 12½%. This alloy is used for both cast and wrought applications. In the case of the wrought alloy only, an addition of Mn of 1-2.5% is usually made, which considerably improves the corrosion resistance.

2. Ternary alloys: Mg-Zn-Mn alloy with 4% Zn and 0.2% Mn.

3. Complex alloys: particularly with Al-Zn-Mn additions, used both for casting and wrought alloys.

4. The above mentioned binary and complex alloys are nowadays sometimes given further small additions of cerium, silicon, copper, cadmium, beryllium and zirconium. Of these Be particularly improves the corrosion resistance and casting properties while Ce and Zr exert a grain refining action.

As further additions, calcium, silver, tin, bismuth, chromium and

<sup>1</sup> = Examples: American alloy 75S, British alloy RR77, Swiss alloy Perunal

nickel are individually added, but so far these are of no great importance.

Owing to its hexagonal crystal structure which permits the deformation of the Mg crystals on one slip-plane only (Fig. 43) the mechanical working of the Mg alloys is found very difficult and deformation is best carried out in a temperature range of 280° to 320° C (536° to 608° F).

In Switzerland, provisional standards have been so far introduced only for the alloys with Al, Zn and Mn. Trade names of the various alloys are tabulated in Table 7a, with compositions and properties in Table 7b.

The casting alloys in general use have as principal constituent 3%, 6% and 9% Al with a few tenths % of Mn and up to 1.5% Zn. The strength increases with rising Al content and the highest alloy with 9% Al is hardenable by heat-treatment (Swiss Pat. 186889, I.G. Farben-Industrie). This last is also much employed for gravity and pressure die castings.

Of the wrought alloys, that with 2% Mn is preferred for rolling into sheets owing to its relatively easy working quality, good corrosion resistance and superior welding properties, while for extrusions and forgings the alloys with 3%, 6% and 8% Al with a few tenths per cent of Mn and up to 2% Zn are

TABLE 6  
COMPOSITION AND MECHANICAL PROPERTIES OF SOME Al-Mg-Zn ALLOYS

Alloy	Composition—%								Proof Stress		Tensile Strength		Elongation %	
	Cu	Mg	Mn	Zn	Ni	Cr	Si	Fe	Ti	Tons/ sq. in.	1000 lb./ sq. in.			
RRR 77 (D.T.D. 687 approx.)	1.5—2.5	2.5—3.0	—	4.5—5.5	0.8	—	0.6	0.6	—	32	72	36	81	11
	2.0 Max	2.0—5.0	—	6.0—14.0	—	—	1.0 Max	0.5 Max	—	34	76	37	83	12
Thom Alloy	1.2—2.0	2.1—2.9	0.1—0.4	5.1—6.1	—	0.15—0.4	0.5	0.7	0.2	32	72	37	83	10
775 S	2.5	2.0	—	6.0	—	0.25	—	—	—	32	72	38	85	14
Perunal	1.0—2.0	1.75—3.0	0.1—0.6	7.0—8.5	—	0.1—0.4	Si + Fe	0.7	—	32	72	38	85	13
Zicral														

TABLE 7a  
TRADE NAMES OF STANDARD MAGNESIUM ALLOYS IN DIFFERENT COUNTRIES

<i>Wrought alloys</i> Alloy	Switzerland	England	U.S.A.	France	Italy	Germany
Mg-3Al	Airal Mg104 Aviomag K3 Elektron AZ31 Maxium GP Maxium 30 Maxium 44 Vallmag GP Vallmag 30 Vallmag 44	Elektron A4	AM 52S AM C52S Downmetal F	F3 T28	Elektron AZ31	Magnasal W383 Elektron AZ31 Magnewin 3512 Magnedur W383
Mg-6Al	Airal Mg107 Aviomag K6 Elektron AZM Maxium 55 Maxium 66 Vallmag 55 Vallmag 66	Elektron AZM Magnuminium 266, 295, 88B	AM 57S AM C57S Downmetal J	M11	Elektron AZM	Elektron AZM Magnewin 3510 Magnedur W386 Magnasal W376
Mg-8Al	Aviomag K8 Maxium 2D Vallmag 2D	Elektron AZ855	AM 58S AM C58S Downmetal O	M3	Elektron AZ855	Elektron AZ855 Magnewin 3515 Magnedur W389 Magnasal W389
Mg-2Mn	Airal Mg100 Aviomag KM Elektron AM503 Maxium 15 Vallmag 15	Elektron AM503 Magnuminium 133	AM 3S Downmetal M	T2	Elektron AM503	Elektron AM503 Magnewin 3501 Magnedur W380 Magnasal W380



TABLE 7a (Continued)

Casting Alloys ("C" for Casting)

Alloy	Switzerland	England	U.S.A	France	Italy	Germany
C: Mg-3Al	Aviomag G3	Elektron AZ31		F3	Elektron AZ31	Elektron AZ31
	Elektron AZ31					
	Maxium GP Vallmag GP					
C: Mg-6Al	Aviomag G6	Elektron AZG	AM 265 AM 266 Dowmetal H	F1	Elektron AZG	Elektron AZG
	Elektron AZG					
	Maxium 2S Vallmag 2G Vallmag 2S					
C: Mg-9Al	Aviomag G9	Elektron AZ91	AM 240 AM 263 Dowmetal G Dowmetal P Dowmetal R	F4 FT	Elektron A9V	Elektron A9V Elektron A8 Elektron A8K Elektron AZ91 Magnewin 3508 Magnewin SG
	Elektron A9V					
	Elektron A8 Elektron A8K Elektron AZ91 Maxium 77X Maxium 2J Maxium 2K Vallmag 77X Vallmag 2J Vallmag 2K					

Most of the names are protected by trade-mark.

used on account of their superior mechanical strength. As the specification shows, the wrought alloys are not generally heat-treated and are employed in the soft or half-hard tempers.

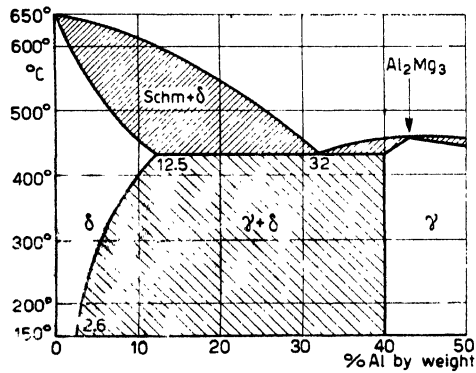


Fig. 42. Equilibrium diagram of Mg-Al alloys.  
Schm +  $\delta$  = Liquid +  $\delta$

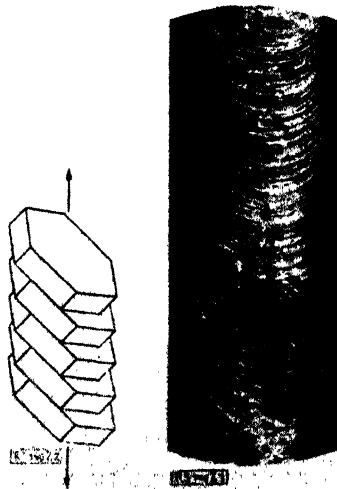


Fig. 43.

Deformation by slip of the hexagonal crystal structure of magnesium alloys  
(W. Schmidt, Zeitschrift für Metallkunde, 1931).

TABLE 7b  
MAGNESIUM ALLOYS

Magnesium casting alloys

Alloy	Composition			Condition	Tensile Strength		Proof Stress		Elongation %	Brinell Hardness	Fatigue Strength 10.10 <sup>6</sup> r Tons/ sq. in.	1000 lb. /sq. in.
	Al	Zn	Mn		Tons/ sq. in.	1000 lb. /sq. in.	Tons/ sq. in.	1000 lb. /sq. in.				
C: Mg-3Al	2.5—3.5	0—1.5	0.1—0.5	Sand cast	9—11	20—24	3—4	7—9	5—10	40—50		
C: Mg-6Al	5—6.5	0—3.5	0.1—0.5	Sand cast	10—13	22—29	6—7	13—16	3—6	45—60		
C: Mg-9Al	7—10	0—1.5	0.1—0.5	Sand cast heat-treated	15—18	34—40	6—8	13—18	7—12	50—65		
C: Mg-9Al	7—10	0—1.5	0.1—0.5	Die cast, not heat-treated	11—15	24—34	6—8	13—18	2—6	50—65		
C: Mg-9Al	7—10	0—1.5	0.1—0.5	Pressure die cast, not heat-treated	11—15	24—34	7—9	16—20	1—3	60—70		

Wrought magnesium alloys

Mg-3Al	1.5—4	0—1.5	0.1—0.5	Not heat-treated	15—18	34—40	9—11	20—24	8—17	45—60	7	16
Mg-6Al	5—6.5	0—1.5	0.1—0.5	Not heat-treated	17—22	38—49	11—13	24—29	10—16	55—70	10	22
Mg-8Al	6.5—9	0—2	0.1—0.5	Not heat-treated	19—22	43—49	13—16	29—36	8—12	60—75	9	20
Mg-2Mn			1.0—2.5	Not heat-treated	12—16	27—36	8—11	18—24	5—12	40—50	5	11

TABLE 7b (Continued)

## Magnesium casting alloys

Alloy	Applications	Specific Gravity	Electrical Conductivity m Ohms mm <sup>2</sup>	% Cu	Temperature coefficient of Resistance (°C)	Coefficient of linear Expansion (°C)	Thermal conductivity Kcal m h °C	Solidification Range		Contraction %
								°C	°F	
C: Mg-3Al	Gas and liquid leak-proof castings . .	1.77	10	17	0.0018	$26.10^{-6}$	90	500—630	932—1166	1.2—1.6
C: Mg-6Al	Castings for fatigue resistance . . . .	1.79	8	14	0.0013	$26.10^{-6}$	80	400—610	752—1130	1.0—1.4
C: Mg-9Al	Fatigue, shock and heat-resisting castings (up to 200°C — 392°F) . . .	1.81	7	12	0.0011	$26.10^{-6}$	70	430—600	806—1112	1.0—1.4
C: Mg-9Al	Gravity die castings . . . . .	1.81	7	12	0.0010	$26.10^{-6}$	70	430—600	806—1112	1.0—1.4
C: Mg-9Al	Pressure die castings . . . . .	1.81	7	12	0.0010	$26.10^{-6}$	70	430—600	806—1112	1.0—1.4

## Wrought magnesium alloys

Mg-3Al	Easily worked alloy for sheets, rods and sections. Can be welded with some difficulty . . . . .	1.77	11	19	0.0018	$26.10^{-6}$	90	500—630	932—1166	
Mg-6Al	Higher strength alloy for rods, sections, tubes, pressings and forgings. Can be welded with some difficulty	1.79	7	12	0.0010	$26.10^{-6}$	70	430—600	806—1112	
Mg-8Al	High strength alloy for pressings and forgings. Can be welded with some difficulty.	1.81	6.5	11	0.0009	$26.10^{-6}$	50	430—600	806—1112	
Mg-2Mn	Corrosion-resistant, weldable alloy for sheets, rods and sections . . . . .	1.78	20	34	0.0036	$26.10^{-6}$	110	645—650	1193—1202	

## CHAPTER III : PROPERTIES AND METHODS OF TESTING

To be able to assess the suitability of a material for a given purpose, we must have knowledge of its properties. Therefore the methods of testing of the light metals are of much importance.

### 1. PHYSICAL PROPERTIES

In Table 8 is given a list of the most important physical properties and their values.

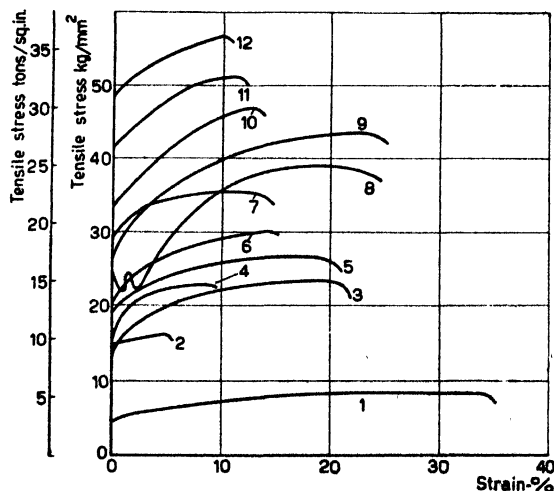
#### a. Static testing

##### (i) Tensile properties

The oldest method of testing materials is probably the determination of the breaking strength, and as tensile loading is that most frequently encountered in use, we will accordingly consider the tensile test first. In this, besides the ultimate tensile stress (or tensile strength), the proof stress (or yield strength), elongation, and sometimes the elastic limit, are determined. It can be seen from the stress-strain curves for Avional, Anticorodal, Peraluman and magnesium-base alloys shown in Fig. 44 with mild steel for comparison, that the light metals have no pronounced in-

Fig. 44. Stress-strain curves of various light metals and mild steel.

- 1 Pure aluminium-soft.
- 2 Pure aluminium-hard.
- 3 Peraluman-3-soft (Al-3Mg).
- 4 Aviomag KM (Mg-2Mn).
- 5 Anticorodal-A (Al-Si-Mg).
- 6 Aviomag K 6 (Mg-6Al).
- 7 Anticorodal-B (Al-Si-Mg).
- 8 Mild steel.
- 9 Avional-D (Duralumin) (Al-Cu-Mg).
- 10 Super-Avional, heat-treated.
- 11 Super-Avional, cold rolled after heat-treatment.
- 12 Alloys 75 S und RR 77 (Al-Mg-Zn-Cu).



flection or yield point between the elastic and plastic conditions. The elastic limit is generally taken as the stress which produces a permanent set of 0.02%, in accordance with the proposal of Prof. LUDWIK of Vienna. This property is designated the 0.02% elastic limit. There is also the 0.2% elastic limit, or yield strength as it is called in America, corresponding to the stress which produces a permanent set of 0.2%. In England the term 0.1% proof stress, although originally introduced to designate in specifications a fixed value of stress for which a 0.1% permanent set should not be exceeded, is now generally used as a synonym for the 0.1% elastic limit, i.e., the stress that produces a permanent set of 0.1%.

TABLE 8

## PHYSICAL PROPERTIES OF 99.5% PURE ALUMINIUM

Atomic weight . . . . .	26.97
Atomic volume . . . . .	10.0
Crystal structure (face centred cubic) lattice parameter cm . . . . .	$4.04 \cdot 10^{-8}$
Specific gravity at 20°C (68°F) . . . . .	2.70
" " " 700°C (1292°F) . . . . .	2.38
Compressibility at 20°C (68°F) . . . . . $dv/v_0$ atmos.	$1.45 \cdot 10^{-6}$
" " " 125°C (257°F) . . . . . $dv/v_0$ atmos.	$1.70 \cdot 10^{-6}$
Surface tension, 700°—800°C (1292—1472°F) . . . . . dynes/cm	520
Coefficient of linear expansion 20°—100°C . . . . .	$24.0 \cdot 10^{-6}$
" " " " 20°—600°C . . . . .	$28.5 \cdot 10^{-6}$
" " " " 68°—212°F . . . . .	$13.4 \cdot 10^{-6}$
" " " " 68°—1112°F . . . . .	$15.7 \cdot 10^{-6}$
Contraction in castings . . . . . %	1.7—1.8
Increase in volume, solid to liquid . . . . . %	about 6.5
Melting point . . . . . °C	658
" " " " °F	1216
Latent heat of fusion . . . . . cal/gm	92.4
" " " " BThU/lb.	166.4
Specific heat at 20°C (68°F) . . . . .	0.214
" " " 100°C (212°F) . . . . .	0.223
" " " 500°C (932°F) . . . . .	0.266
Average specific heat, 0°—658°C (32°—1216°F) (Solid) . . . . .	0.25
Specific heat at 700°C (1292°F) . . . . .	0.25
Boiling point . . . . . °C	2270
" " " " °F	4100
Vapour pressure at 659°C (1218°F) . . . . . mm Hg	0.00062
" " " 700°C (1292°F) . . . . .	0.001
Thermal conductivity at 0°C . . . . . cal/cm/sec/°C	0.50
" " " 100°C . . . . .	0.51
" " " 200°C . . . . .	0.52
Lorentz coefficient (for 99.6% Al) . . . . .	$5.46 \cdot 10^{-6}$
Electrical conductivity at 20°C (68°F) Soft m/Ohm.mm <sup>2</sup> . . . . .	36—36.5 (62-63% Cu)
" " " Hard " . . . . .	35—35.5 (60-61% Cu)
" " " Cast " . . . . .	About 33
" " " 660°C (1220°F) molten " . . . . .	4
Specific electrical resistance at 20°C (68°F) Soft Ohms.mm <sup>2</sup> /m . . . . .	0.0278—0.0274
" " " Hard " . . . . .	0.0286—0.0282
" " " Cast " . . . . .	about 0.03
" " " 660°C (1220°F) molten " . . . . .	0.25
Temperature coefficient of electrical resistance, solid (°C) . . . . .	0.0041
Heat of combustion . . . . . kcal per gramme atom oxygen	133

TABLE 8. (Continued)

Electrochemical equivalent . . . . .	gm/amp.h	0.3354
Electrolytic solution potential at 20°C in aerated 20% NaCl solution against normal calomel electrode . . . . .	mvolt	-740 to -750
Thermo-electric power against platinum . . . . .	mvolt/100°C	+0.41
Magnetic susceptibility at 18°C . . . . .		$0.6 \cdot 10^{-6}$
Young's modulus of elasticity . . . . .	tons/sq. in	$4000 \times 4300$
" " " " . . . . .	lb./sq. in	$9 \cdot 10^{-6} - 9 \cdot 7 \cdot 10^9$

For the determination of the 0.02% elastic limit, the usual autographic stress strain record is insufficiently accurate, but the sensitive autographic recorder developed by Alfred J. Amsler & Co., Schaffhausen (Fig. 45)

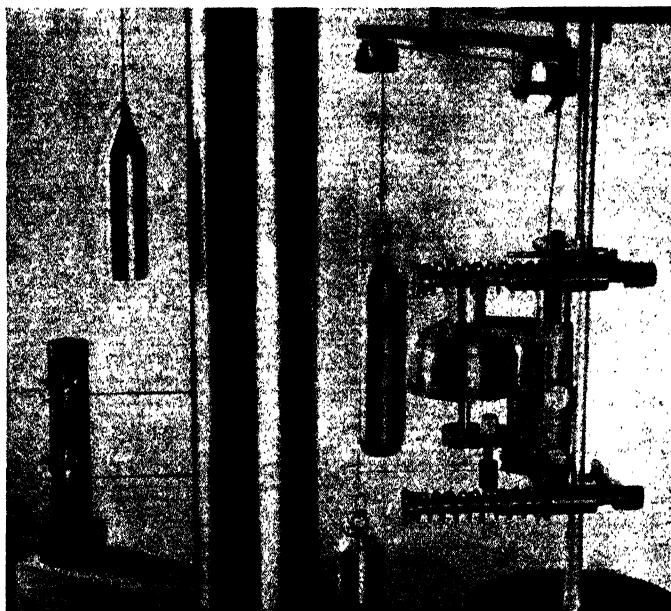


Fig. 45. Extensometer for strain measurement in tensile testing (Alfred J. Amsler & Co. Schaffhausen, Switzerland).

is quite suitable. In the determination, the speed of loading should be such that fracture takes place in 1 to 3 minutes, as with much slower speeds of the order of 10 to 30 minutes, appreciable divergence of the results takes place as shown in Fig. 46 due to creep of the material. For still more accurate measurements, there are the OKHUIZEN tensometer by HUGGENBERGER and the MARTENS mirror extensometer.

The plastic flow which precedes fracture is generally concentrated in a short region of the test piece, as shown in Fig. 47, so that the greatest

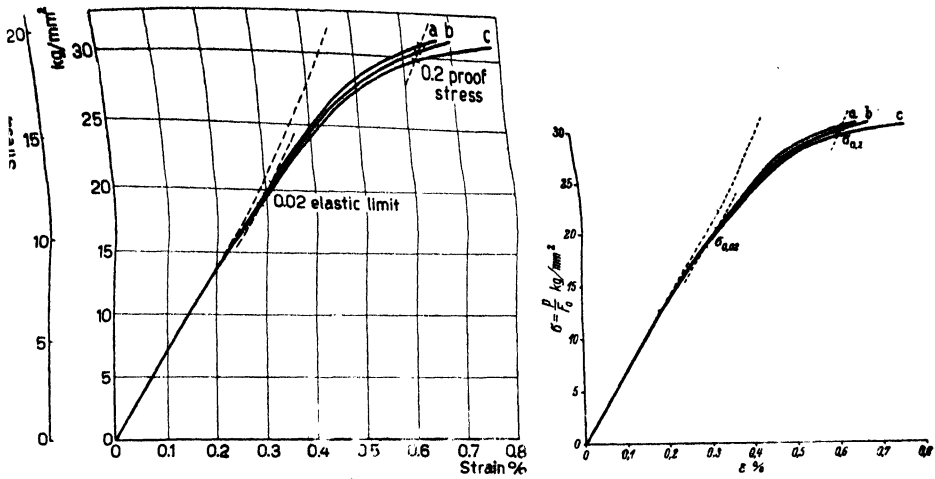


Fig. 46. Effect of rate of loading on the stress-strain curve of Avional (Al-Cu-Mg).  
a 2 min, b 10 min, c 30 min loading time to fracture.

elongation takes place in this region. For this reason the shorter the gauge length on which the elongation is measured, the higher the value of percentage elongation obtained. Fig. 48 shows the effect of the gauge length of different standard test pieces on the resulting elongation for one and the same material, i.e., pure aluminium.

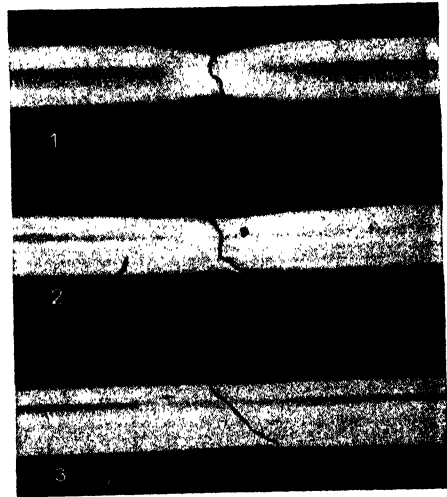


Fig. 47. Necking at fracture of tensile test-pieces.

- 1 Anticorodal (Al-Si-Mg) soft.
- 2 semi-hard (quenched only).
- 3 maximum hardness (quenched and warm aged).

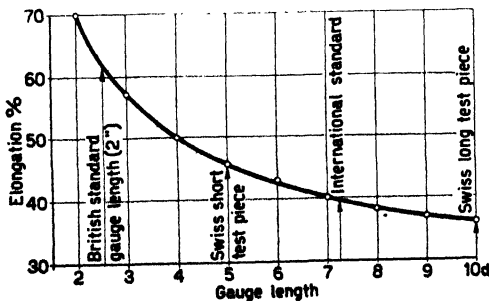


Fig. 48. Gauge length and elongation of soft pure aluminium, test pieces 12 mm diam.



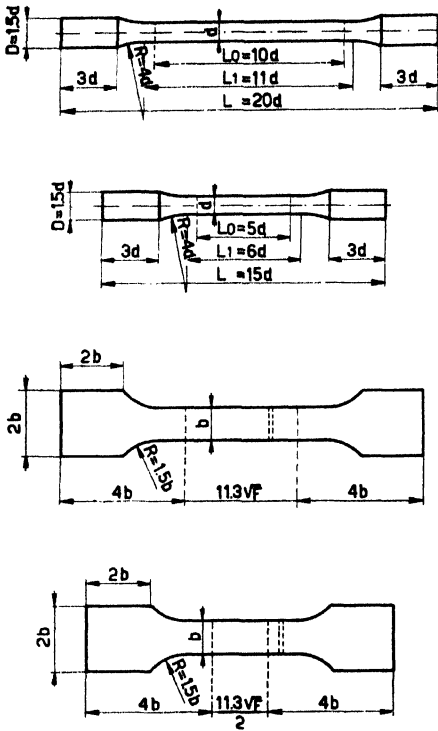


Fig. 49. Dimensions of "proportional" test piece.

Above — round test pieces.  
Below — flat test pieces.

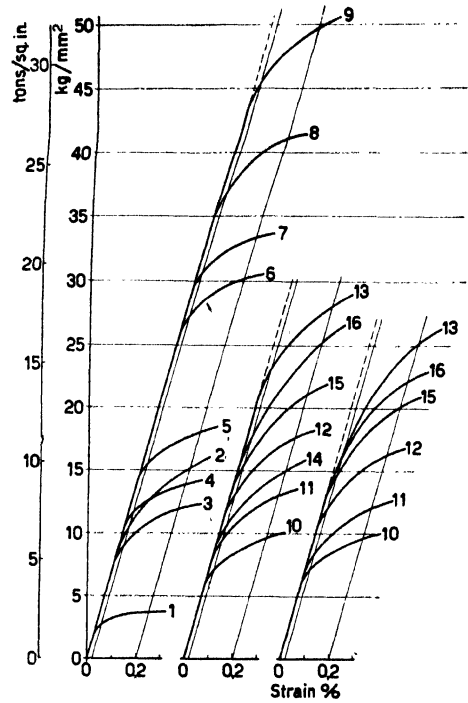
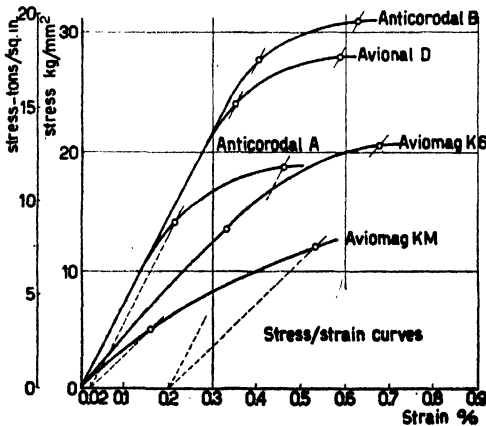


Fig. 50. Stress-strain curves of some common aluminium alloys.

- Left — wrought.  
Centre — Gravity die cast.  
Right — Sand cast.
- 1 Pure aluminium soft.
  - 2 Pure aluminium hard.
  - 3 Peraluman-3 (Al-3Mg) soft.
  - 4 Peraluman-5 (Al-5Mg) soft.
  - 5 Anticorodal (Al-Si-Mg) semi-hard.
  - 6 Anticorodal fully age hardened.
  - 7 Avional (Al-Cu-Mg) age hardened.
  - 8 Superalvional warm aged and cold rolled.
  - 9 Alloy 75 S (U.S.A.).
  - 10 Peraluman-5 (C: Al-5Mg).
  - 11 Anticorodal (as cast) C: Al-Si-Mg.
  - 12 Anticorodal semi-hard.
  - 13 Anticorodal hard.
  - 14 Alufont as cast (C: Al-Cu-Mg).
  - 15 Alufont-3 hard.
  - 16 Alufont-4 hard.

Fig. 51. Stress-strain diagram of wrought aluminium and magnesium alloys (Avional Al-Cu-Mg and Alumag).

This shows up the substantially greater value of elongation given by the British two-inch test piece, since this has the smallest ratio of gauge length to cross-sectional area.

In order therefore to get comparable values of elongation, the ratio of initial cross-sectional area of the test piece " $A_0$ " to the gauge length must be constant. Test pieces which conform with this requirement are called proportional test pieces. Fig. 49 shows the recommended dimensions of proportional test pieces for aluminium. For the sake of economy in material, a ratio of gauge length " $l$ " to cross-sectional area of  $l = 5.65 \sqrt{A_0}$  is used, and this test piece is called the short proportional test piece on account of its lesser length. For more accurate measurements, the long (double length) test piece with  $l = 11.3 \sqrt{A_0}$  is used, and with this, as explained above, a somewhat smaller elongation is obtained than with the short test-piece.

Conversion factors for metric to British stress units are given in Table 9.

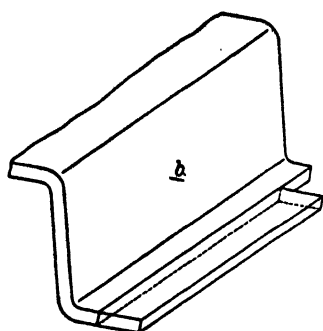
TABLE 9

## CONVERSION FACTORS FOR STRESS UNITS

1 lb. per square inch	= $7.031 \cdot 10^{-4}$ kg per mm <sup>2</sup>
1 ton per square inch	= 1.575 kg per mm <sup>2</sup>

Fig. 50 shows the 0.2% proof stress or yield strength and the 0.02% elastic limit of aluminium and its light alloys. The different characteristics of the aluminium and magnesium alloys are revealed in Fig. 51. Here the smaller modulus of elasticity of the magnesium alloys as compared with those of aluminium is clearly seen in the lesser slope of the curves in the elastic range.

Wrought material generally displays a high uniformity of property, but in cast parts, frequently even in the same casting, widely different properties may sometimes be registered according to the position of the test piece. This is exemplified by Table 10, which shows the mechanical properties of a cast lorry wheel in Silumin and Alufont 3. With Silumin Gamma the 0.2% proof stress registered varied from 10 to 19 tons /sq. in. (22 000-43 000 lb./sq. in.) and the tensile strength from 15 to 20 tons/sq. in. (34 000—45 000 lb./sq. in.) with an elongation of 0.9 to 1.7 %. This wheel was a favourable piece for casting, with uniform section except for the hub, while casting conditions were satisfactory. With greater differences of section a much greater degree of variation may occur. The accurate determination of tensile strength is therefore much more problematical with castings and only systematic destructive test on an entire casting, as in the foregoing example, can give complete information. It is therefore incorrect to draw conclusions on the strength of a casting from tests on



separately cast or cast-on test pieces. The strength of separately cast as well as cast-on test pieces and runners (see Fig. 52) merely serve to indicate the quality of the molten alloy that is used for the production of the casting, for which purpose the separately cast test piece is to be preferred owing to its simpler production.

Fig. 52. Cast-on test piece.

TABLE 10

MECHANICAL TEST RESULTS ON A CAST "GF" <sup>1</sup> "TRILEX" WHEEL IN SILUMIN (C: Al-12Si) AND ALUFONT3 (C: Al-Cu-Ti)

	0.2% Proof Stress		Tensile Strength		Elongation %				Brinell Hardness	
	Tons/sq. in. (1000 lb./sq. in.)		Tons/sq. in. in brackets)		Long test piece		Short test piece			
Web 11 tests	S	A	S	A	S	A	S	A	S	A
min . . . . .	13.0 (29.6)	14.3 (32.0)	15.6 (35.0)	20.1 (45.0)	0.6	3.2	0.9	4.0	89	90
max . . . . .	20.2 (45.3)	16.2 (36.3)	20.4 (45.7)	21.4 (47.4)	0.9	6.4	1.7	7.7	111	97
mean . . . . .	17.3 (38.8)	15.4 (34.5)	18.2 (40.8)	20.3 (45.5)	0.7	4.8	1.2	5.6	93	94
Rim 4 tests										
min . . . . .	10.4 (23.3)	10.8 (24.2)	18.0 (40.3)	18.0 (40.3)	0.7	3.9	0.8	5.2	95	90
max . . . . .	17.3 (38.8)	15.7 (35.2)	18.6 (41.7)	21.4 (45.7)	—	6.5	1.3	7.5	105	97
mean . . . . .	13.9 (31.2)	13.6 (30.4)	18.3 (41.0)	19.7 (44.2)	—	4.8	1.0	6.1	99	92
Hub 12 tests										
min . . . . .	—	11.6 (26.0)	—	12.4 (27.8)	—	0.5	—	1.0	—	84
max . . . . .	—	15.0 (33.6)	—	16.9 (37.9)	—	1.8	—	2.8	—	94
mean . . . . .	—	13.7 (30.7)	—	15.4 (34.5)	—	1.2	—	1.8	—	91
Guaranteed values in separate test pieces										
min . . . . .	14.0 (31.4)	11.4 (25.6)	15.9 (35.6)	16.5 (37.0)	0.5	4.0	—	—	80	80
max . . . . .	17.8 (39.9)	14.0 (31.4)	20.3 (45.5)	20.3 (45.5)	4.0	8.0	—	—	100	90
	S = Silumin		A = Alufont 3							

Fig. 53 illustrates the best method of casting sand cast test pieces, the result of many years' investigations. The down-gate enters the runners through a long notched skimming gate, while at the other end of the test

<sup>1</sup> The George Fischer Steel & Iron Works, Ltd., Schaffhausen, Switzerland.

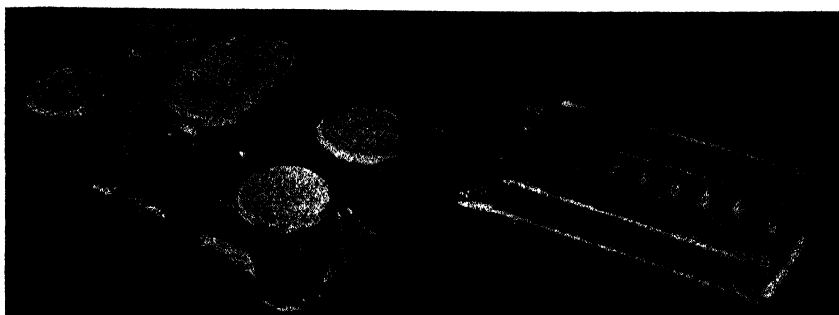


Fig. 54. Moulding practice for magnesium sand-cast test piece.

Fig. 53. Moulding practice for aluminium sand-cast test pieces.

pieces a small individual riser is taken up from each one. The mould arrangement for the more commonly used magnesium alloys is shown in Fig. 54. With these, big risers are necessary at both ends of the casting if soundness is to be obtained. Fig. 55 shows various chill moulds for the casting of chill cast test pieces. As the casting conditions in sand and chill moulds are very different, the test piece must in all cases be cast in the same type of mould as the casting it is to represent. In large quantity casting jobs, it is essential to determine at the outset the best arrangement of gates and risers and the correct casting conditions by tensile tests on the casting itself. When once this is settled, it is sufficient thereafter to check the metal quality by means of separately cast test pieces.

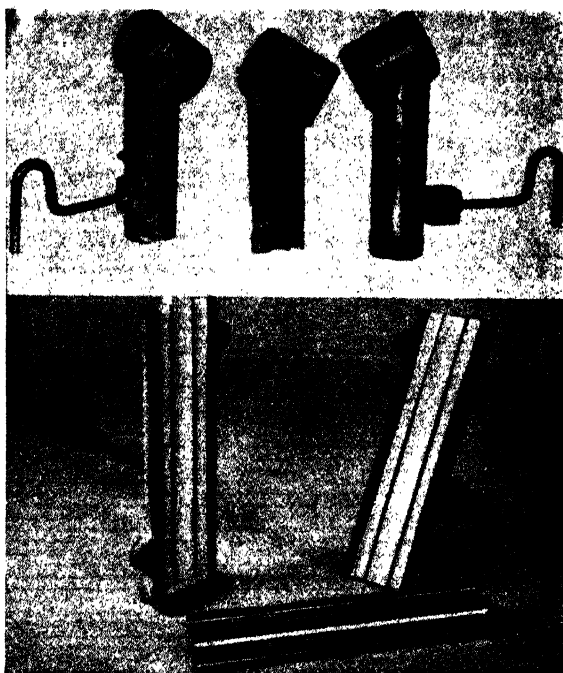


Fig. 55. Chill moulds for casting test bars.

### (ii) *Modulus of elasticity*

The modulus of elasticity is of much importance in bending and compression members. In contrast with the value of Young's modulus for

steel of about 13 400 tons/sq. in. ( $30 \cdot 10^6$  lb./sq. in.), that for pure aluminium and its alloys is about 3 800-4 800 tons/sq. in. ( $8.5-10.8 \cdot 10^6$  lb./sq. in.), and that for magnesium and its alloys 2 600-2 730 tons/sq. in. ( $5.8-6.0 \cdot 10^6$  lb./sq. in.).

The modulus of elasticity is only slightly affected by variations in composition or by cold working, as it follows on the atomic volume and melting point and is a structure-insensitive property<sup>1</sup>. The lower modulus of the light metals implies a correspondingly greater elastic strain or extension in cases such as the bending of beams, which must generally be compensated for by an increase in the moment of inertia of the section. By virtue of their low specific gravity this can usually be arranged for without impairing their economy. Against shock loads, their lower modulus of elasticity permits a higher loading for light metals than for heavy metals.

### (iii) Hardness

For a hardness test, it is sufficient to provide a clean flat surface of only about 1 centimetre square, and the test can be carried out without destroying the piece tested. In the case of the light metals, however, it is to be noted that no constant relationship exists between the properties of hardness and tensile strength, so that a hardness test cannot properly be used as a substitute for a tensile test. Nevertheless the hardness test is of great use in the control of precipitation hardening. The hardness test in most general use is the Brinell test, in which a hard steel ball is pressed into the test piece under a specified load. From the surface area of the spherical impression made by the ball, and the applied load, the Brinell hardness is computed in kg/mm<sup>2</sup>. During the penetration of the ball, a work-hardening of the material takes place and for this reason a predetermined ratio of ball diameter to applied load must be maintained, while the load should be applied on the ball for a period of 30 seconds. For aluminium a kilogramme load equal to  $5d^2$  is recommended,  $d$  being the diameter of the ball in millimetres. This rule gives a load of 500 kg for a 10 mm, 125 kg for a 5 mm, and 31.2 kg for a 2.5 mm diameter of ball. The 5 mm ball is used for sheets under .080 in. thick, the 2.5 mm ball for sheets under .040 in. Below .040 in., especially with soft tempered metal, the Brinell hardness is not reliable. The magnitude of the applied pressure depends on the hardness of the material as well as on the specific loading. With greater hardness or smaller specific loading, a shallow impression is obtained, while conversely with a lower hardness or greater load, in extreme cases the impression is almost hemispherical. It was formerly considered sufficient to observe a certain ratio between ball diameter

<sup>1</sup> LEON GUILLET JR, Paris 1939 Doctorate Thesis.

and load, irrespective of the hardness of the material. Furthermore, the ratio of ball diameter to sheet thickness has an effect, so that some scatter of results is to be observed in the ordinary Brinell test. If instead of the ball, a penetrating body of such shape that a geometrically similar impression is produced for different depths of impression, as with the LUDWIG pointed cone or the VICKERS pyramid, the effect of different depths of impression on the recorded hardness is eliminated. With the Brinell test, an increasing test load gives an increase in recorded hardness up to a maximum beyond which the recorded hardness begins to fall off again. By using a load on the ball such that the diameter of the impression is about 0.4 times that of the ball, and if the minimum sheet thickness tested is not less than 0.4 times the ball diameter, so that the ratio of the sheet thickness to the depth of impression is not smaller than 10, it is possible with the Brinell test to obtain hardness values as uniform as in the VICKERS pyramid test. Microtests for hardness have been developed recently using a diamond point with which the hardness of a small area of only about 1 sq.mm can be determined. This makes possible the determination of the hardness of separate phases in alloys, usually termed the microhardness.

#### (iv) Impact strength

For the determination of the notched-bar impact strength, or toughness, of light metals, a pendulum hammer of 35 to 110 foot lbs. kinetic energy (5-15 mkg) is used, and the height of swing is so chosen that after the fracture of the test piece the residual energy is not excessive. To avoid losses by friction with the test piece, the edges of the vice or the supports are rounded with a  $3/32$  in. radius. The dimensions of the test piece shown in Fig. 56 are in accordance with the Swiss V.S.M. Specification 10910. Aluminium casting alloys have notched-bar strengths of 1.4-7 ft.-lb. (0.2-1 mkg), heat-treated wrought alloys 14 to 29 ft.-lb. (2-4 mkg), while common wrought alloys may exceed 70 ft.-lb. (10 mkg), all measured on the 1 cm square test piece. The magnesium casting alloys run from 2-3.6 ft.-lb. (0.3-0.5 mkg) and the wrought alloys from 5.8-6.6 ft.-lb. (0.8-0.9 mkg.)

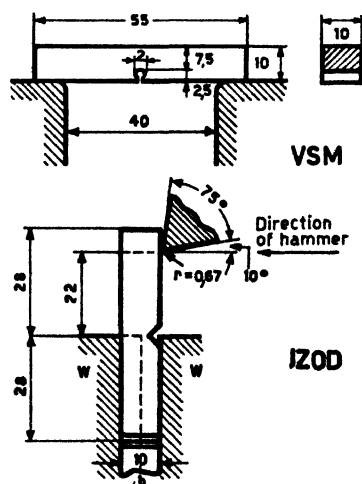


Fig. 56. Notched impact test bar.

Above VSM.  
Below British.

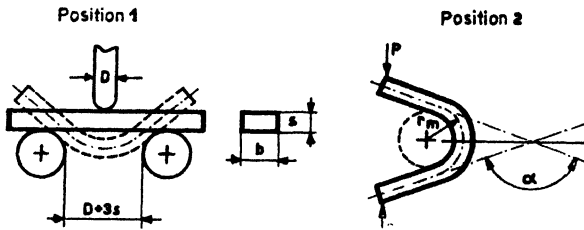


Fig. 57. Bend test on flat bars.

(v) *Bending tests*

The static transverse or bending test is carried out on flat test pieces as shown in Fig. 57. In the bend or folding test for sheets the edges of the test specimens are rounded, but in the static transverse bending test they are square. In the bend test for sheet specimens, the bending is done slowly and steadily in a press, generally to start with around a feather or laminar punch, as in the initial stage of the static bending test, then by pressure on the free side, the test piece is pressed together until a crack begins to develop on the outer surface of the bend. The angle of bend is measured in accordance with the V.S.M. specification as shown in the illustration. Transverse tests are of particular interest to small foundries which frequently do not have a tensile testing machine available, but which can carry out control tests on their castings by means of a transverse bending test, using an improvised rig or a simple dynamometer as shown

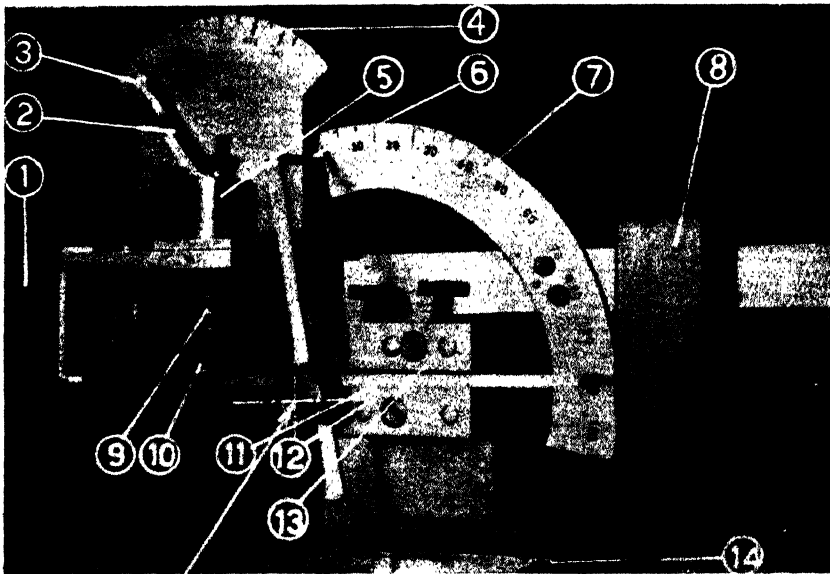


Fig. 58. Dynamometer for bending test on cast bars.

- |                             |                         |                          |
|-----------------------------|-------------------------|--------------------------|
| 1 Lever arm.                | 6 Bend angle indicator. | 11 Bend test piece.      |
| 2 Load indicator.           | 7 Bend angle scale.     | 12 Lower champing cheek. |
| 3 Bending moment indicator. | 8 Counterweight.        | 13 Upper champing cheek. |
| 4 Bending moment scale.     | 9 Load spring.          | 14 Vice.                 |
| 5 Spring housing.           | 10 Stop plate.          |                          |

in Fig. 58. The size of the bending test piece used is  $5 \times 10 \times 100$  mm.

In testing sheet and wire, a reversed bend test is often carried out in a longitudinal and particularly a transverse direction relative to the direction of rolling. In this the radius of bend is 5 or 2.5 times the sheet thickness and the sheet is bent both ways to a right-angle. A  $90^\circ$  bend and return to the straight counts as one bend. Fig. 59 shows a reversed bend testing machine for sheet test pieces.

(vi) *Deep drawing tests*

The Erichsen test is frequently used to give an indication of the working property of sheets in respect of spinning, pressing and drawing. It must be realized that this particular test does not provide an absolute value for the capacity to withstand deep drawing, as the action of a draw press cannot be readily reproduced on a small scale. As shown in Fig. 60, the various light alloys have very different Erichsen indentation values, and the effect of sheet thickness on the depth of indentation is not the same with all alloys. In the case of Avional or Duralumin (Al-Cu-Mg alloy), the rate of increase of indentation value with the increase of sheet thickness is surprisingly small in comparison with the softer alloys. Fig. 61 shows a sectional elevation of the Erichsen testing machine. A ball shaped punch 20mm diameter is pressed into a sheet test piece clamped between holding rings, up to the point where the first sign of fracture is seen to occur in the dome. The depth of indent or dome at that stage is taken as the Erichsen value. The appearance of the surface of the dome provides an indication of the grain size of the material, coarse grained sheets giving domes with a rough surface. Furthermore the appearance of the annular fracture gives an indication of the homogeneity of the sheet. With greatly different tensile properties in the longitudinal and transverse directions in the sheet, the annular fracture becomes out of round. Such sheets tend to form

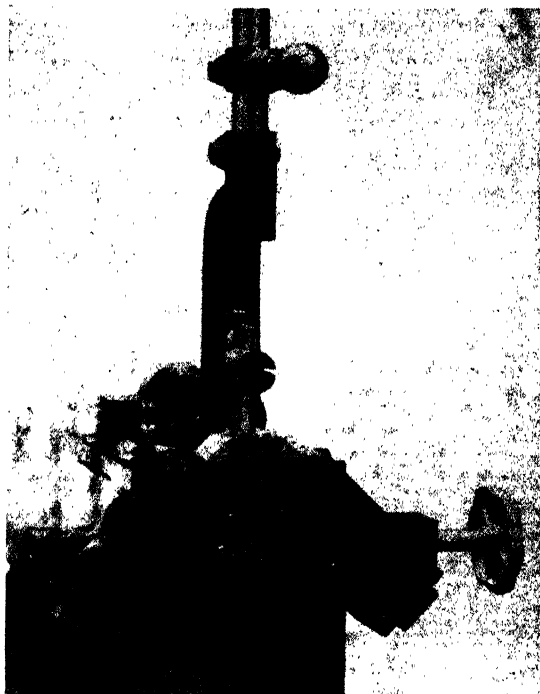


Fig. 59. Reverse bending sheet testing machine. (Alfred J. Amsler, Schaffhausen, Switzerland).



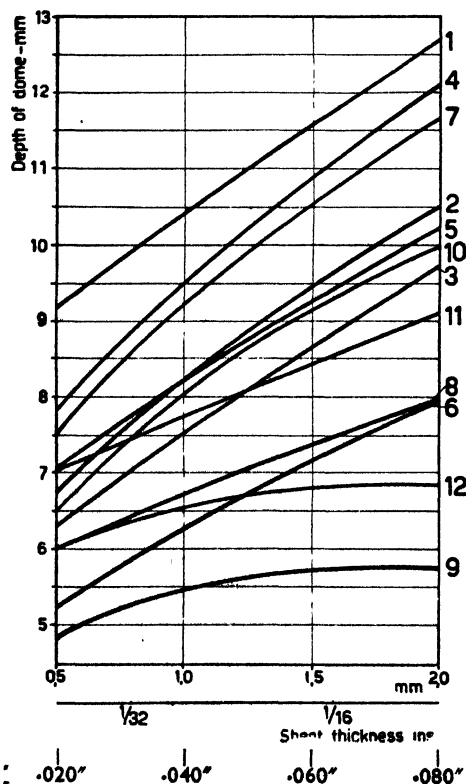
ears in spinning and pressing (see Chapter XII on deep drawing).

For a more reliable test of the deep drawing property, a miniature drawing die set is now used, as in Fig. 62, which shows a die-set for drawing a cylindrical cup, and with which redraws can be carried out also. This arrangement gives more reliable indications of the deep drawing properties than the Erichsen test, but is distinctly more complicated to apply.

### b. Strength at extreme temperatures

#### (i) Elevated temperatures

For the determination of tensile strength at elevated temperatures, a small heating furnace for the test piece is attached to the tensile testing machine, as shown in Fig. 63. To find the true value of the property under these conditions for any material it is necessary for the test piece to be maintained at the temperature of the test for a period of time sufficiently long to ensure that no further diminution of strength takes place. For this reason it is usual for the test piece to be held in a separate annealing furnace at the test temperature prior to the actual test and finally to be transferred to the testing machine furnace. Figs. 33-35 shows the effect of prolonged heating on the strength of various alloys.



prolonged heating on the strength of various alloys.

Owing to their rather low melting points, appreciable loss of strength occurs in the light alloys on heating to a relatively low temperature. The highest safe working temperature for light alloys is from 230°-300° C (482°-572° F). Even this is only permissible in certain applications, such as motor pistons. In the case of the age-hardened alloys, a loss of strength takes place on prolonged heating at 100°-130° C

Fig. 60. Erichsen indentation values of various alloys.

- 1 Pure aluminium, soft.
- 2 Pure aluminium, half-hard.
- 3 Pure aluminium, hard.
- 4 Aluman (Al-Mn), soft.
- 5 Aluman, half hard.
- 6 Aluman, hard.
- 7 Anticorodal (Al-Si-Mg), soft.
- 8 Anticorodal, semi hard.
- 9 Anticorodal, hard.
- 10 Peraluman (Al-Mg), soft.
- 11 Avional (Duralumin, Al-Cu-Mg), annealed.
- 12 Avional-D, heat-treated.

(212°-266° F), and this constitutes their safe working temperature in most cases. Avional or Duralumin (Al-Cu-Mg) commences to lose strength at 120° C (248° F), Anti-corodal (Al-Si-Mg) at 100° C (212° F); thus the former alloy can be used satisfactorily at somewhat more elevated temperatures than the latter. In the case of Avional, the effect of short time heating at limited temperatures is of interest, this providing a good illustration of the complexities of the precipitation hardening process (Fig. 64). We perceive from this, that at a temperature of 160° C (320° F),

a low point of tensile strength occurs after 4 hours' heating, while after 48 hours at this temperature the tensile strength attains a second maximum. Precipitation hardening is completed at this stage and a final softening consequent on the coalescence of the copper-bearing precipitate follows. The first softening may be used to facilitate cold forming, following which the material may be restored to its original strength by the necessary

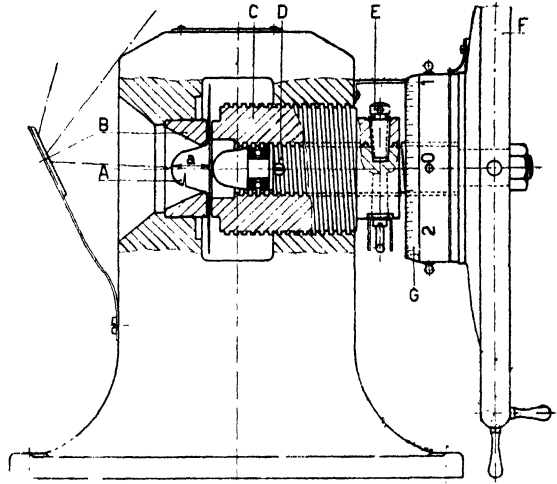


Fig. 61. Erichson indentation testing machine.

- |                      |                 |
|----------------------|-----------------|
| A Test piece.        | E Coupling pin. |
| B Die ring.          | F Hand wheel.   |
| C Blank holder ring. | G Index scale.  |
| D Punch.             |                 |

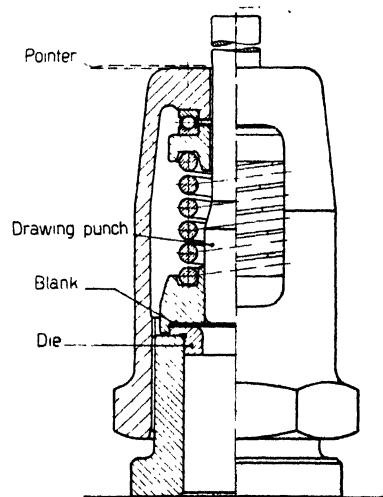
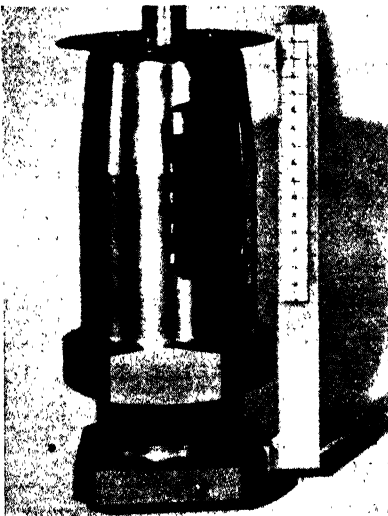


Fig. 62. Miniature die set for deep-drawing tests (after von Burg, AIAG).

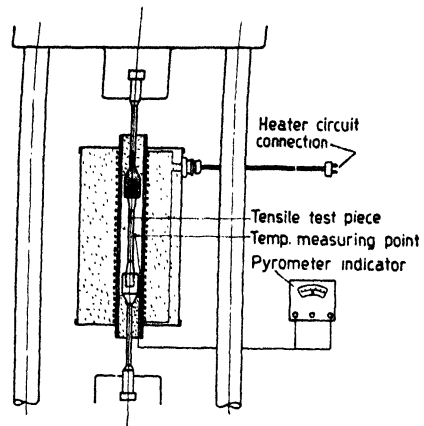
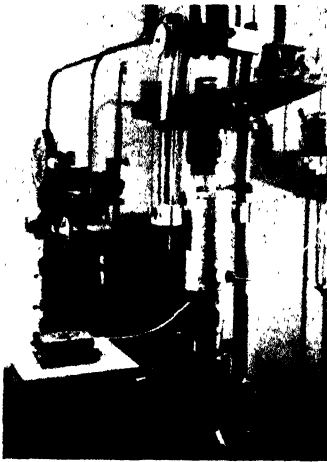


Fig. 63. Furnace for determination of tensile strength at elevated temperature.

further such low temperature heating. The process is termed short-time low-temperature heat-treatment. This process has an effect not only on the strength, but on the electrochemical solution potential also (Fig. 36).

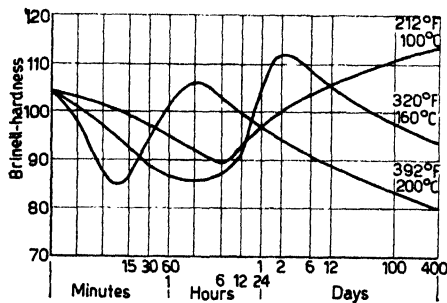


Fig. 64.

Effect of short-time heating on the tensile strength of Avional (Duralumin) (Al-Cu-Mg).

The reduction of strength at elevated temperature is of paramount importance in hot-working processes such as forging, hot rolling and extrusion. In the case of cold working, a prior medium temperature anneal is often given in order to lessen the resistance to deformation, the hardening being afterwards carried out by a final solution heat-treatment and quenching.

### (ii) Subzero temperatures

In contrast to many heavy metals in which a falling-off of strength occurs at subzero temperatures, with cold-embrittlement, in the case of aluminium

alloys, as shown in Fig. 65, there is an increase of toughness and notched bar impact strength, and at the same time a small increase in tensile strength. This fact is important and of advantage in aircraft, overhead cables and vehicles, which are frequently in service under conditions of subzero temperatures.

### c. Endurance

ALBERT in 1829 was the first to recognize in chain cables the incidence of fracture under repeated loading much below the static breaking strength, and FAIRBAIRN in 1850 constructed the first fatigue testing machine, while WÖHLER in the '60's laid the foundations of modern fatigue testing. The importance of fatigue strength was only generally recognized in the present century, and systematic researches were begun. Of greater importance than static endurance or creep strength, is the endurance under fluctuating loads or fatigue strength, owing to the more destructive effect of the latter conditions.

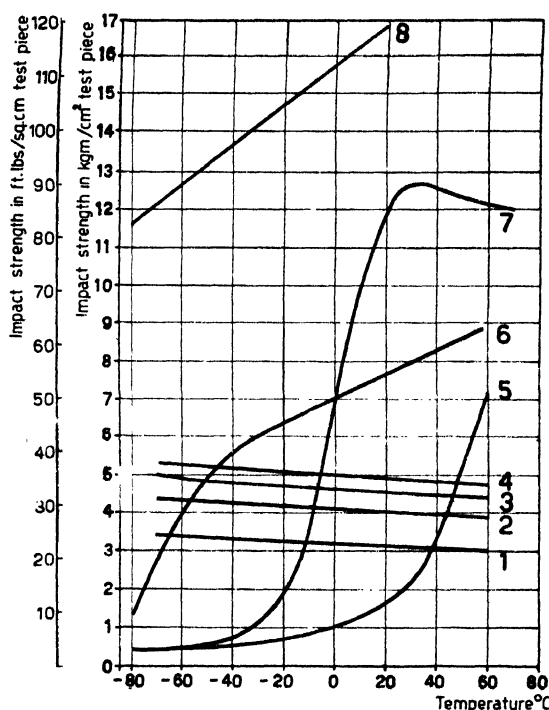


Fig. 65. Effect of subzero and elevated temperatures on notched bar impact strength.

- 1 Avional D (Duralumin, heat-treated) (Al-Cu-Mg).
- 2 Anticorodal A (Al-Mg-Si).
- 3 Peraluman-2 (Al-Mg-Mn).
- 4 Peraluman-7 (Al-7Mg).
- 5 Mild steel, artificially aged.
- 6 Cu-Mn-Si steel, annealed.
- 7 Mild steel, annealed.
- 8 Cr-Mn-Si austenitic steel.

### (i) Creep strength

In long-time tensile or creep testing, it would appear to be a desirable thing to determine the strength at indefinite time, or creep strength, by an abbreviated method. It is found, however, that reliable results cannot be obtained in this way. It is obligatory to prolong the test for at least 1000 hours to obtain a reliable determination of the creep strength. Usually a large number of test pieces under various loads are set up simultaneously so that after 1000 hours the lightest loaded do not exceed the permitted extension of 0.0001% per hour. Fig. 66 shows curves of creep strength

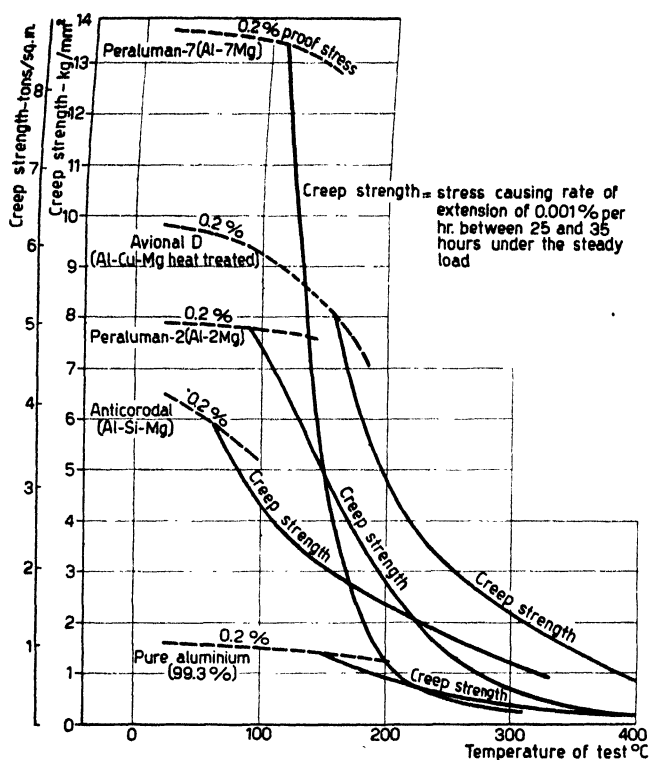


Fig. 66. Creep strength of stabilised wrought aluminium alloys at elevated temperatures.

for different aluminium alloys at elevated temperatures. These curves represent a collection of limiting values of the creep curves for different stressings at equal temperatures, the short-time elastic limits at elevated temperatures being shown with broken lines.

As the light metals are frequently used in service at somewhat elevated temperatures it is necessary to determine the values of creep strength at elevated temperatures. For this the specimens are tested in special

furnaces under simultaneous heating and tensile loading. Fig. 67 shows such an apparatus, with arrangements for maintaining both the temperature and the loads constant.

Beside tensile creep at elevated temperatures, the behaviour of hardness under similar conditions is important in cases such as motor pistons. For this endurance hardness test, a ball is impressed into the material under a predetermined load (Fig. 68), as in the Brinell test. In this

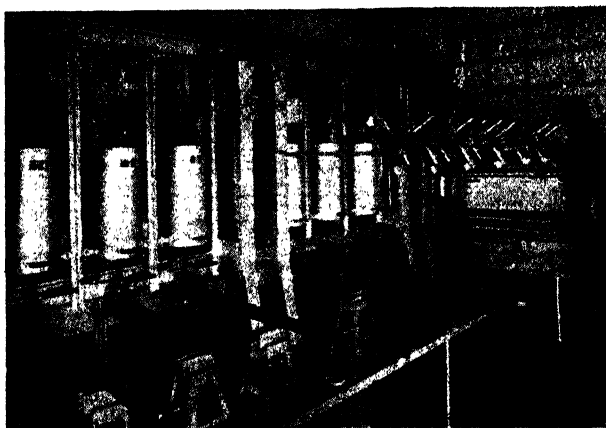


Fig. 67.  
Creep testing apparatus for elevated temperatures.

case also the test piece is placed in a furnace at constant temperature and the constant load is maintained until no further penetration occurs. Fig. 69 shows that alloys of somewhat similar compositions have marked differences in endurance hardness at elevated temperatures. In particular, the content of nickel in Y alloy has a favourable effect in this respect.

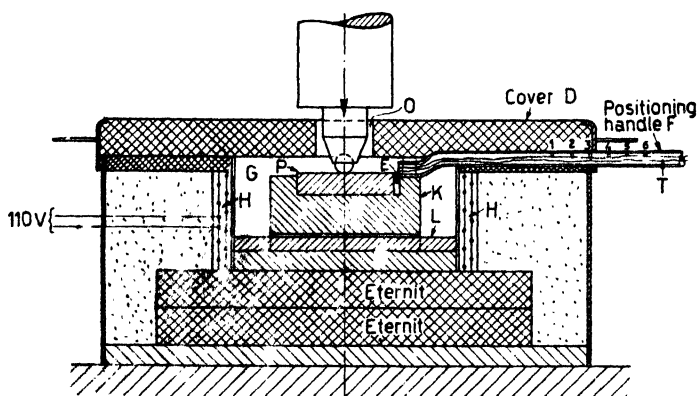


Fig. 68. Apparatus for determination of endurance hardness at elevated temperatures.

D = Eternit cover (asbestos composition).	P = Test specimen.
F = Positioning handle.	G = Heating chamber.
E = Temperature measuring point.	K = Specimen holder (steel).
T = Thermocouple.	L = Plate carrying specimen holder.
1—5 = Graduation on positioning handle.	H = Heaters.

### (ii) Endurance under dynamic conditions (fatigue)

We distinguish 6 basic conditions of fatigue, namely:

1. Alternating<sup>1</sup> tensile
2. Alternating<sup>1</sup> compression
3. Alternating tensile compression
4. Alternating<sup>2</sup> bending
5. Alternating<sup>1</sup> torsion
6. Repeated impact

The alternating bending fatigue test is the simplest to apply, in which, on a machine such as the Wöhler

<sup>1</sup> or Repeated      <sup>2</sup> or Reversed

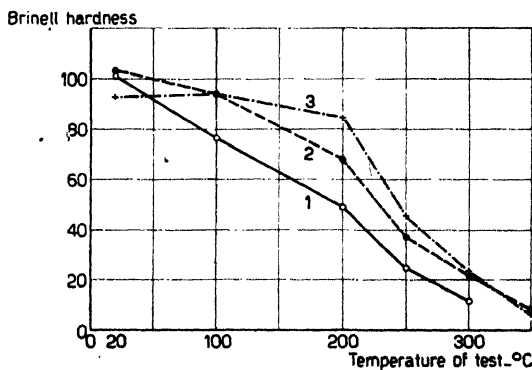


Fig. 69. Hardness of heat-treated wrought aluminium alloys, incompletely homogenised, after 2 hours at testing temperature.

- 1 Anticorodal (Al-Si-Mg).  
 2 Avional D (Duralumin) (Al-Cu-Mg).  
 3 Y-alloy (Al-Cu-Ni).

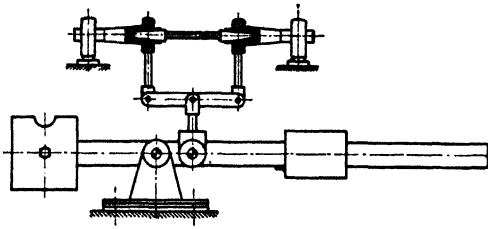


Fig. 70. Arrangement of Wöhler rotating beam type fatigue testing machine.

flaws in the surface may act as the starting point of a fatigue fracture and cause an abnormally low fatigue strength to be registered. In systematic testing, carefully ground and polished test pieces should be used. The effect of the surface condition on the fatigue strength is shown in Fig. 71. Beside alternating<sup>1</sup> bending, zero to maximum conditions of alternating<sup>2</sup> direct stress are also used in testing, as well as minimum to maximum unidirectional alternating<sup>2</sup> stressing, the last named implying a static load with a superimposed alternating load (Fig. 72).

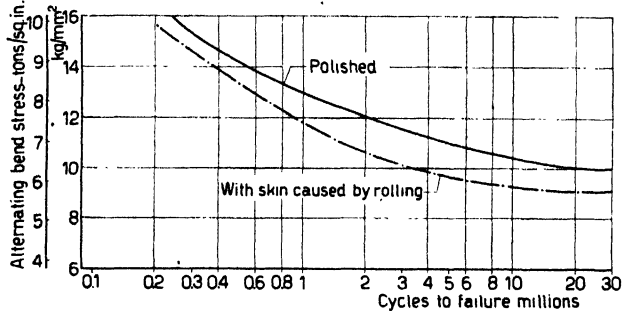
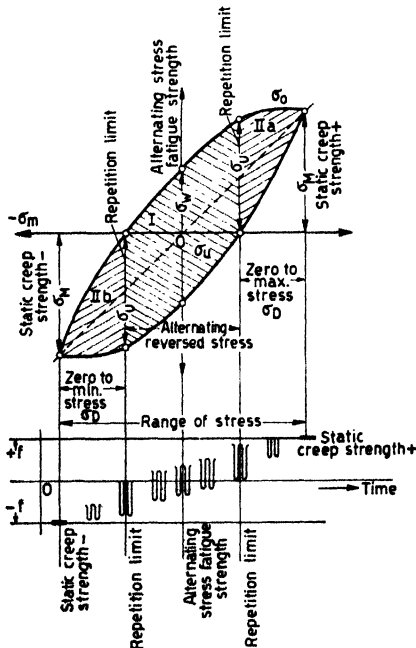


Fig. 71. Effect of surface finish on the apparent fatigue strength of Avional (Duralumin) (Al-Cu-Mg).



testing, as well as minimum to maximum unidirectional alternating<sup>2</sup> stressing, the last named implying a static load with a superimposed alternating load (Fig. 72).

In the fatigue testing of sheet material, an alternating tensile test, or a flat bending test as in Fig. 73 are employed.

The frequency or speed of the fatigue testing machine is an important consideration in endurance testing as loading cycles may run into many millions. Exhaustive tests have demonstrated that the frequency may be increased to 500 cycles per second without effect on the endurance curve.

<sup>1</sup> or reversed    <sup>2</sup> or repeated

Fig. 72.

Comparison of various fatigue loading conditions.

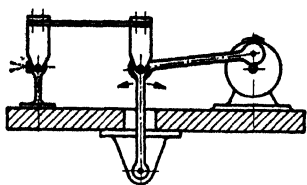


Fig. 73. D.V.L. sheet fatigue bending-machines.

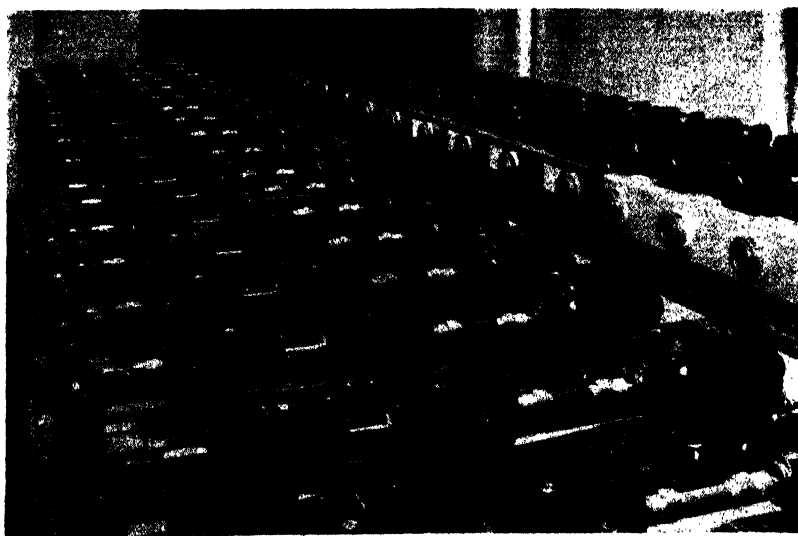
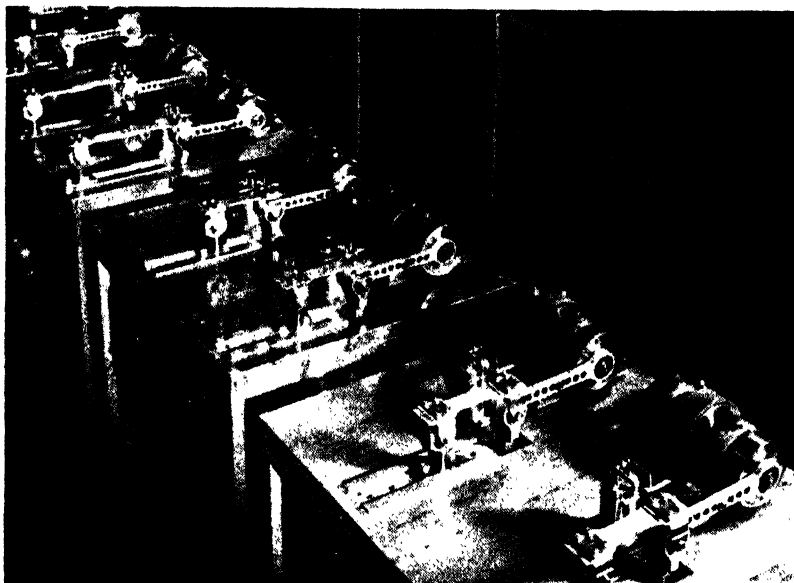


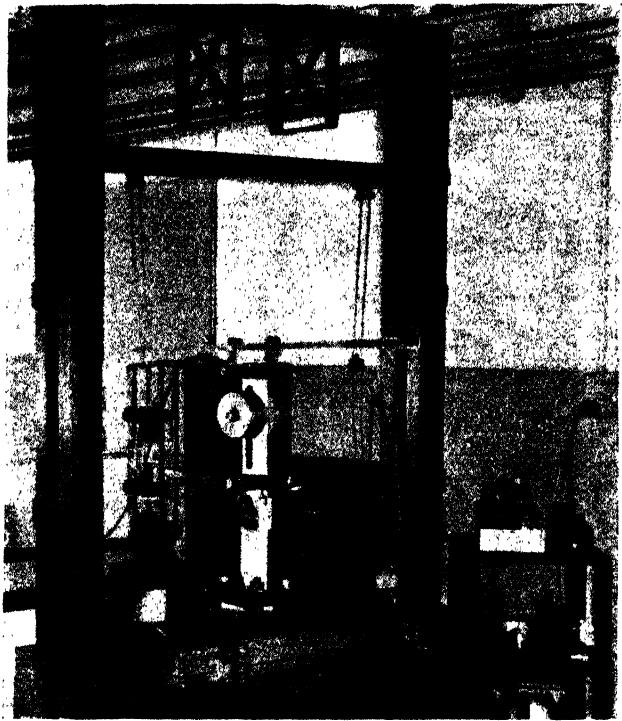
Fig. 74. Fatigue testing-machines. Top: in the A.I.A.G. Laboratories at Neuhausen. Bottom: in the New Kensington Laboratories of the Aluminium Company of America.



Fig. 75. Alternating bending stress fatigue testing machine for structural members (resonance type)—after W. Müller, A.I.A.G.

A series of graded loadings, each applied to at least 3 to 5 test pieces are necessary for the determination of a complete endurance curve, and thus a considerable number of fatigue testing machines are required to obtain a result on any one material in a reasonable time (Fig. 74).

If a fatigue test



piece or an element of a structure is loaded first to a low alternating stress, and if this stress is increased at a later time, an apparent increase of the fatigue strength will be observed, a phenomenon known as training up the material. In obtaining an accurate endurance curve, it is therefore not permissible to use any test pieces unbroken after testing at a lower stress for a further test to failure at a higher stress.

Fig. 76a. Electrical resonance type direct stress fatigue testing machine (Alfred J. Amsler, Schaffhausen, Switzerland).

Since the fatigue strength for a given composition and a given degree of work-hardening only varies within narrow limits, it is not used as a control test in the course of manufacture of the metal, but, like the modulus of elasticity, it is regarded as a constant of the material.

For the alternating direct tensile-compression test, several different machines have been proposed, some utilising the effect of resonance, which has the advantage of using a much smaller power.

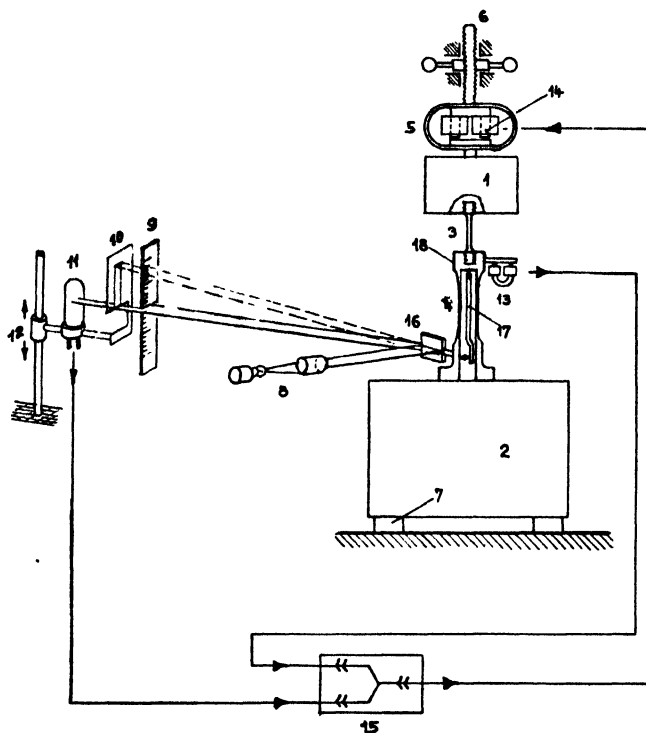


Fig. 76b. Diagram of high frequency stress pulsator (Alfred J. Amsler and Co., Schaffhausen, Switzerland).

- |                                   |                             |
|-----------------------------------|-----------------------------|
| 1 Vibrating mass.                 | 10 Diaphragm.               |
| 2 Counter mass (anvil).           | 11 Photo electric cell.     |
| 3 Test piece.                     | 12 Photo cell mounting.     |
| 4 Dynamometer for measuring load. | 13 Control generator.       |
| 5 Preloading spring.              | 14 Operating magnet.        |
| 6 Preloading screw.               | 15 Amplifier.               |
| 7 Rubber foot pads.               | 16 Mirror bar.              |
| 8 Projection lamp system.         | 17 Comparison bar.          |
| 9 Dynamometer scale.              | 18 Lower grip for specimen. |

For testing entire elements of structures, a resonant whirling machine has been developed by W. MÜLLER in the Research Laboratories of the Aluminium-Industrie A.G., Switzerland, on which systematic investigations can be carried out, for example on riveted joints of bridge members and vehicle frames, as in Fig. 75.

TABLE 11

STATIC AND DYNAMIC MECHANICAL PROPERTIES OF SOME WROUGHT ALUMINIUM ALLOYS.  
ROTATING BEND TESTS ON EXTRUDED RODS (10, 20 & 60 MILLION REVERSALS OF STRESS)

Alloy Type	Alloy Designation and size	Treatment	0.02% Elastic Limit Tons/sq. in.*	0.2% Proof Stress Tons/sq. in.*	Tensile strength Tons/sq. in.*	Elongation in 11.3 in. %	Brinell Hardness	Fatigue strength Tons/sq. in.*		
								10 million cycles	20 million cycles	60 million cycles
Al-Cu-Mg	Avional 22 M .91 inch dia.	Cold aged.	24.0 (54)	24.6 (55)	32.1 (70)	15.3	112	12.1 (27.1)	11.2 (25.1)	10.1 (22.4)
Al-Cu-Mg	Avional 411 .87 inch dia.	Warm aged	21.8 (49)	25.3 (57)	29.2 (65)	11.9	135	10.2 (22.8)	9.7 (21.7)	9.2 (20.4)
Al-Cu-Mg	Avional D .87 inch dia.	Solution heat-treated, cold drawn from 1.38 to .87 inch dia., cold aged.	15.7 (25)	16.4 (27)	27.1 (61)	22.7	—	11.1 (24.6)	10.4 (23.3)	9.5 (21.3)
Al-Si-Mg	Anticorodal A .87 inch dia.	Solution heat-treated, & warm aged 1½ hrs. at 160°C. (320°F)	10.4 (23.3)	11.4 (25.5)	17.9 (40)	23.0	82	7.6 (17.0)	7.1 (15.9)	6.1 (13.7)
Al-Si-Mg	Anticorodal B .87 inch dia.	Warm aged	19.5 (44)	20.6 (46)	22.3 (50)	10.4	110	7.5 (16.8)	6.8 (15.2)	5.9 (13.0)
Al-Si-Mg	Anticorodal B .87 inch dia.	Solution heat-treated, cold drawn 1.38 to .87 inch dia., warm aged	17.2 (39)	19.2 (43)	23.4 (52)	13.3	113	10.3 (23.1)	9.7 (21.7)	8.9 (19.9)
Al-Mg	Peraluman 2	As extruded	7.0 (17.4)	7.8 (17.5)	16.3 (26.7)	14.0	55	8.6 (19.2)	8.3 (18.6)	7.8 (17.5)

\* 1000 lb./sq. in. in brackets

Fig. 76a shows a new electrical resonance fatigue testing machine by Alfred J. Amsler & Co. for alternating direct tensile-compression tests, which can be run up to 100 cycles per second and takes an electric power of 200 watts. The principle of the action of this resonance testing arrangement is illustrated diagrammatically in Fig. 76b.

Table 11 gives a comparison of the static and dynamic mechanical properties of some aluminium alloys.

#### d. Other physical properties

##### (i) Contraction

Solid contraction is an important property in castings. In the aluminium alloys this runs from 1.15 % for Silumin (Al-12Si) to 1.75 % for pure aluminium, which compare with 1.04 % for cast iron, 1.5 % for brass and 2.0 % for cast steel. In the case of magnesium and its alloys, the contraction runs between 2 % for the pure metal and 1.0 to 1.6 % for the magnesium alloys. This factor is of special importance in die castings, as the metallic mould is completely unyielding, and if the contraction of the alloy is high there is a tendency for cracks to be formed in the casting. For this reason the casting alloys in general use have a maximum contraction of 1.4 %. The contraction of an alloy is generally measured by casting a test piece in an accurately machined Invar steel mould, the difference of length of the test piece and the mould, after cooling, compared with the length of the mould giving the measure of the contraction.

TABLE 12  
MEAN COEFFICIENTS OF LINEAR EXPANSION

	20° to 100°C per° C	68°—212°F per° F	20° to 200°C per° C	68°—392°F per° F
Pure aluminium	23.8·10 <sup>-6</sup>	13.4·10 <sup>-6</sup>	24.7·10 <sup>-6</sup>	13.7·10 <sup>-6</sup>
Al-Mg-Mn (Peraluman 2) . . .	23.6	13.2	24.3	13.5
Al-Cu-Mg(Avional, Duralumin)	22.9	12.7	24.4	13.6
Al-Mg-Si (Anticorodal rolling alloy) . . . . .	22.7	12.6	23.3	13.0
Al-Cu-Ni (Y alloy) . . . . .	22.5	12.5	23.9	12.8
Al-Si (Silumin) . . . . .	19.0	10.5	21.0	11.7
Lo-Ex (Piston alloy) . . . . .	18.6	10.3	19.8	11.0
Iron . . . . .	12.5	6.9	12.7	7.1
Copper . . . . .	16.5	9.2	16.7	9.3
Zinc . . . . .	31.0	17.2	38.0	21.1
Pure magnesium . . . . .	25.9	14.4	26.5	14.7
Mg-3Al wrought . . . . .	26.1	14.5	27.1	15.1
Mg-6Al wrought . . . . .	26.0	14.4	27.3	15.2
C: Mg-6Al sand cast . . . . .	26.4	14.7	27.6	15.3
C: Mg-9Al die cast (gravity) .	26.4	14.7	27.4	15.2
Mg-2Mn wrought . . . . .	26.1	14.5	26.9	14.9

### (ii) *Thermal expansivity*

The expansivity of the light metals is distinctly greater than that of most heavy metals. This must be allowed for in composite assemblies and structures composed of different materials, owing to the stresses that may arise with change of temperature. Table 12 gives the average coefficients of linear expansion for some aluminium and magnesium alloys and some heavy metals.

### (iii) *Melting point*

The pure metals have higher melting points than the alloys, that of aluminium being  $657^{\circ}\text{C}$  ( $1215^{\circ}\text{F}$ ) and magnesium  $651^{\circ}\text{C}$  ( $1204^{\circ}\text{F}$ ). The eutectic alloys have the lowest melting points, for example the Al-Cu eutectic  $548^{\circ}\text{C}$  ( $1018^{\circ}\text{F}$ ), Al-Si  $577^{\circ}\text{C}$  ( $1071^{\circ}\text{F}$ ) and Mg-Al  $425^{\circ}\text{C}$  ( $797^{\circ}\text{F}$ ). The ternary eutectics melt lower still. For this reason the complex alloys Al-Cu-Ni and C: Al-Zn-Cu (casting alloy) have a melting range between  $530^{\circ}\text{C}$  and  $640^{\circ}\text{C}$  ( $986^{\circ}$ - $1184^{\circ}\text{F}$ ). The greater the melting range, the stronger is the tendency of the alloy to segregate during the process of solidification. Thus from the standpoint of foundry practice, the eutectic alloys with a solidification point are to be preferred to the solid solution alloys with a solidification range. When the solidification takes place very rapidly, as in die-casting or water-casting, the segregation is suppressed and a fine grained structure results. When segregation occurs, the solidus point of the first portion of the alloy to melt is lower in comparison with that of the homogeneous alloy. In solution heat-treatment of castings of such alloys it is therefore essential that the material be given time for homogenization by slow heating, up to 24 hours in duration.

### (iv) *Conductivity*

Just as the pure metals possess the highest melting point, so also do they exhibit the highest electrical and thermal conductivity. These properties are considerably reduced by alloying, and also by cold work and heat-treatment to varying degrees. The most adverse effect is produced by the presence of titanium and manganese. Fully soft-annealed or stabilised alloys have a greater conductivity than the same alloys in a cold-worked condition, or in a solution heat-treated, quenched and aged condition. The electrical and thermal conductivities do not vary quite the same as each other, so that for accurate information, the thermal conductivity must be determined directly.

Aluminium of 99.5% purity in the as cast condition shows a thermal conductivity of 0.506 cal/cm. sec°C, while after a homogenising anneal this increases to 0.513, and by cold work (e.g., cold forging) it decreases to 0.489. In comparison Avional (Al-Cu-Mg) shows 0.265 as cast, 0.407 homogenised, and 0.304 cal/cm. sec°C after forging and heat-treatment. The thermal conductivity of magnesium over the range 0 to 100°C is 0.40 cal/cm. sec°C, that of the magnesium alloys being 0.22 to 0.25.

## 2. CHEMICAL PROPERTIES — CORROSION

In spite of its great affinity for oxygen, aluminium has a remarkable power of resistance to many corrosive conditions. Thus aluminium cables have resisted the action of the weather for over 50 years even in pronounced coastal or urban atmospheres. Again, aluminium has stood up faultlessly to service as a roofing material without special protection (see p. 8). The reason for this lies in the oxide skin which, under the influence of the oxygen of the atmosphere, forms instantly on bare aluminium and, by reason of its imperviousness to moisture and gases, protects the underlying metal against further attack. Also the base or electropositive characteristics of aluminium are appreciably lessened by the oxide skin, and thus the metal is virtually raised to a more noble level in the electrochemical series. It can in general be said that aluminium is only attacked if its oxide skin is removed or penetrated by some chemical, electrolytic or mechanical means.

Magnesium which generally is much more susceptible to corrosion than aluminium, has a surprisingly high corrosion resistance against hydrofluoric acid, while in general it is less attacked by alkalis and common salt than the aluminium alloys.

As in other metals, the corrosion resistance increases with the purity. The impurities in ordinary virgin aluminium, mainly iron and silicon, in the quantities usually present, only affect the corrosion resistance slightly. On the other hand, copper in quite a small quantity begins to have an adverse effect on the corrosion resistance, while nickel, silver, chromium and titanium act somewhat similarly, Zinc only begins to have a detrimental effect in contents over about 1%. Manganese and magnesium in aluminium act to a certain extent as inhibitors of corrosion, magnesium being particularly efficacious against saline waters such as sea water. When the magnesium content exceeds 5%, its effect may be adversely effected by intercrystalline precipitation of the magnesium. To counteract this a special heat-treatment is necessary to improve the corrosion resistance. Some elements, such as antimony, form a protective film in incipient corrosive action, and reinforce the protective action of the oxide film. In magnesium alloys, manganese particularly acts as a corrosion inhibitor.

Electrolytic magnesium can be brought to the highest purity by redistillation and this markedly improves its corrosive resistance.



Fig. 77. Corrosion pit due to local galvanic action.

In recent years, as in the cases of copper and zinc, super purity aluminium, or "Raffinal", of 99.99% purity has been successfully produced, and this has an extremely high resistance to corrosion. By alloying this with equally pure magnesium, zinc, silicon and manganese, alloys of the Peraluman and Anticorodal types can be obtained which possess not only high mechanical properties as in Table 13, but in addition, after suitable heat-treatment, show a high resistance to corrosion by many corrosive chemical liquids. These alloys have for this reason interesting possibilities of application in chemical apparatus. Since

super purity aluminium or Raffinal is considerably more expensive than virgin pure aluminium, it is advantageously used for cladding ordinary aluminium alloys with a super purity base alloy of high corrosion resistance, a coating thickness of 10% being generally used on one side only.

Three different types of corrosive attack may be distinguished, as follow:

1. General corrosion, the metal surface being uniformly removed by chemical solution of the oxide skin.
2. Local corrosion or pitting. This is always electrochemical in nature, consequent on the existence of local galvanic couples, as a result of which the corrosion penetrates deeply over a small area (Fig. 77).
3. Intercrystalline corrosion. This type also is electrochemical in nature and is due to galvanic couples. It differs from pitting in that the cause is not relatively large particles of foreign metal, but microconstituents precipitated in the grain boundaries on solidification or in subsequent heat-

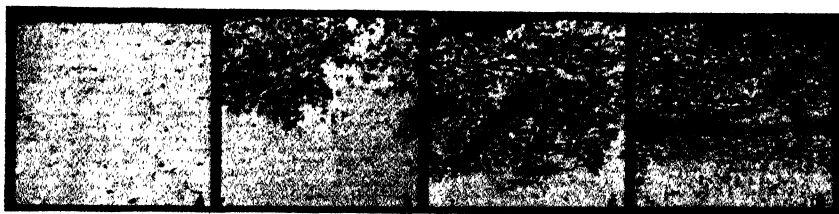


Fig. 78. Examples of intercrystalline corrosion in Avional (Al-Cu-Mg alloy) — Effect of delay before quenching which permits precooling.

A 10 secs interval, B 20 secs, C 30 secs, D 60 secs.

TABLE 13

COMPOSITION, MECHANICAL PROPERTIES AND CORROSION TESTS OF ALUMINIUM ALLOYS WITH SUPER PURITY ALUMINIUM (RAFFINAL) BASES, WITH 99.5% ALUMINIUM AND ANTICORODAL B FOR COMPARISON

Alloy designation	Composition — %						Mechanical Properties Let-down or warm-aged			Gas-volumetric solubility test in 5% NaOH and 10% HCl*				Solubility in H <sub>2</sub> SO <sub>4</sub> and HNO <sub>3</sub> . Loss of weight in gm/sq.in./day (1—600 hrs.)							
	Fe	Si	Cu	Zn	Mg	Mn	Tensile Strength		Elong- ation %	Brinell Hard- ness	Reaction no. <sup>1</sup> in 5% NaOH		Reaction no. <sup>1</sup> in 10% HCl		20% H <sub>2</sub> SO <sub>4</sub>		5% HNO <sub>3</sub>		25% HNO <sub>3</sub>		
							Tons /sq. in.	Lb. /sq. in.			Homo- genised	Let down	Homo- genised	Let down	Homo- genised	Let down	Homo- genised	Let down	Homo- genised	Let down	
Super purity Al (Raffinal)							3.2	7	50	14	3.3	3.5	.010	.011	1.3	1.3	2.0	2.0	5.3	5.3	
Anticorodal (Al-Si-Mg)	.0100	1.02	.0012	—	.952	.487	23.4	52	12	105	3.7	4	.012	.011	1.6	2.0	4.0	4.8	10.2	12.3	
Peraluman 5 (Al-5Mg with- out Mn)	.0029	.0074	.0013	—	4.97	—	13.3	30	28	63	4.2	4.0	.028	.15	2.5	6.8	5.7	*	11.7	*	
Peraluman 7 (Al-7Mg)	.0108	.0128	.0013	—	6.11	.432	20.4	44	25.5	78	5.7	5.9	.055	1.85	3.3	*	4.9	*	11.5	*	
1.5% Mg <sub>2</sub> Si	.0030	.48	.0011	—	.80	—	21.9	49	11.5	105	1.2	1.1	.013	.012	1.6	1.2	2.7	3.0	6.2	6.4	
3% Mg Zn <sub>2</sub>	.0014	.0032	.00125	2.57	.48	—	5.4	12	21.5	25	4.4	4.3	1.75	1.72	2.4	1.8	1.8	2.2	3.3	6.3	
6% Mg Zn <sub>2</sub>	.0019	.0034	.00125	4.99	.982	—	14.3	32	14	72	4.7	4.8	3.0	3.1	2.4	2.1	2.1	2.1	2.8	*	
99.5% pure aluminium							5.1	11	35	22	6—8	—	5—15	—	2—3	—	2—4	—	5—7	—	
Anticorodal B (Al-Si-Mg)	<0.4	1	<0.02	—	0.7	0.7	22.2	50	12	100	—	6—8	—	5—15	—	2—3	—	4—6	—	10—15	

\* Disintegrated

$$\text{Reaction number} = \frac{\text{cc H}_2 \text{ at NTP}}{\text{hrs.} \times \text{sq. cm of surface}}$$



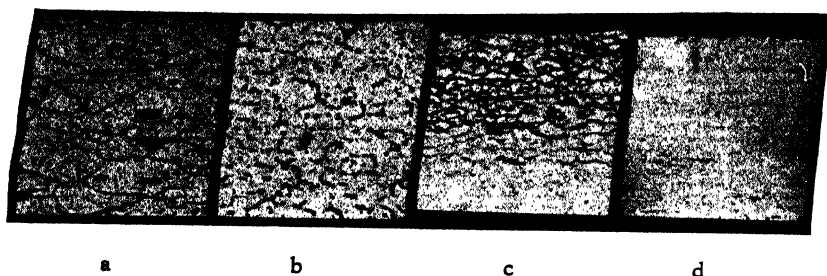


Fig. 79. Effect of thermal treatment on corrodibility of Peraluman (Al-Mg alloy)

- (a) Homogenised.
- (b) Homogenised 310°C (590°F) and heterogenised at 250°C (482°F).
- (c) "a" subjected to corrosive conditions
- (d) "b" subjected to corrosive conditions.

treatment. If the precipitate differs in solution potential from the surrounding metal, then under the influence of an electrolyte (a conducting liquid) galvanic couples are set up, the constituents in the grain boundaries are dissolved and an almost invisible and deeply penetrating deterioration of the metal takes place on a broad scale (Fig. 78).

The corrosion of the aluminium-magnesium alloys is typical of this type. When the Mg content exceeds the limit of solubility in aluminium, a precipitate of  $Mg_2Al_3$  is formed at the grain boundaries on cooling. This compound is less noble than the Al-Mg solid solution, and becomes the anode and is dissolved in the electrolyte (Fig. 79). By appropriate thermal treatment, the precipitate can be caused to agglomerate in the form of discrete particles (string-of-pearls structure) in the grain boundaries.

To achieve this, the  $Mg_2Al_3$  must be brought into solid solution by annealing at 310° C (590° F), and the alloy must then be heterogenised by slow cooling for 10 hours to 250° C (482° F). The supersaturated  $Mg_2Al_3$  is reprecipitated with a string-of-pearls structure in the grain boundaries. With this structure, only those particles of precipitate at the surface are dissolved and the corrosion attack comes to a standstill.

With the supersaturated copper-containing alloys, such as Avional, or Duralumin, the phenomenon is reversed. In this case the  $CuAl_2$  precipitate formed at the grain boundaries on warm ageing is more noble than the surrounding

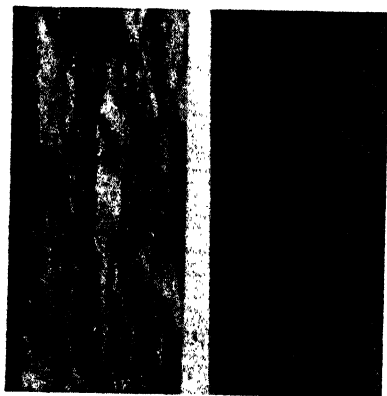


Fig. 80. Effect of thermal treatment on the corrodibility of an Al-Mg-Zn-Mn alloy, immersed 1½ months in 3% NaCl solution.

Left: hard rolled.

Right: annealed.

metal and is therefore not dissolved. The electrolyte on the other hand in this case causes an attack on the metal surrounding the precipitates. Thus there is in this case no advantage in the string-of-pearls structure in retarding intercrystalline corrosion. It is therefore essential with such alloys that no precipitate is formed at the grain boundaries.

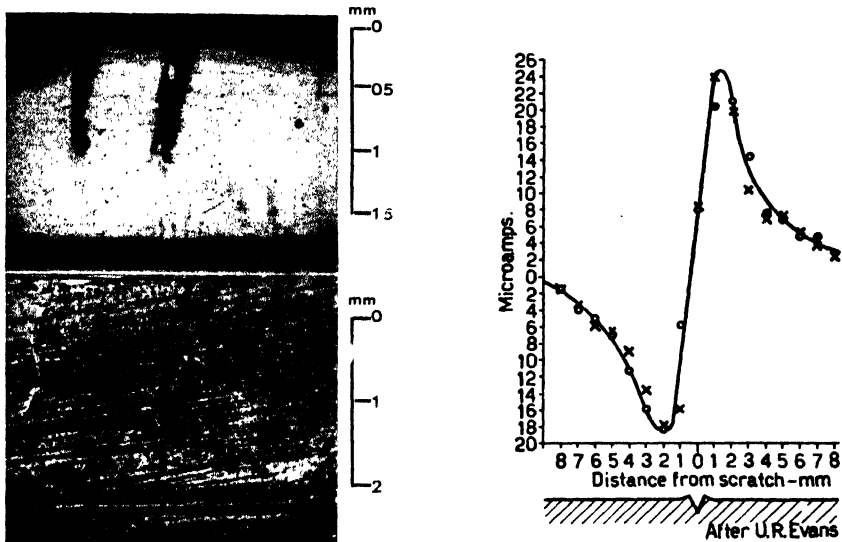


Fig. 81. Local corrosion originating in surface defects.

This condition can be achieved by rapid quenching after solution heat-treatment, as illustrated in Fig. 78. In the case of thin sheets, a delay of as little as 30 seconds between the heat-treatment furnace and the quenching tank will result in the precipitation of  $\text{CuAl}_2$  which will give a condition prone to intercrystalline corrosion. A warm ageing treatment subsequent to the solution treatment has a similar effect to the delayed quench, so this process is only suitable for use with material that is clad with pure aluminium or Anticorodal (Al-Si-Mg alloy). The coating effectively protects the underlying corrosion-susceptible Avional against attack by electrolytes, and thus the superior mechanical properties obtainable by artificial or warm ageing can be made use of with the retention of a good corrosion resistance.

Since the coating is electrochemically less noble than Avional, it is capable, in case of surface damage in which the coating is locally penetrated, of protecting the exposed Avional by a protective action at some distance. With some sheet rolled alloys, the unavoidable heterogeneity of the rolling block causes a laminar condition which may be prone to fissure corrosion

as in Fig. 80 if homogenisation by thermal treatment has not been complete. A rough surface condition favours corrosion, as concentration differences can be built up in an electrolyte in any crevices or depressions, which may cause galvanic effects and consequent local corrosion. Fig. 81, lower left, shows the surface of a scratched sheet, while above is seen a deep local attack of crevice corrosion penetrating the section. The scale of the illustrations is shown in both cases. The right half of the illustration shows the measurement after EVANS of the galvanic current in microampères.

#### a. Corrosion Testing

Corrosion testing is rather a difficult matter. Generally speaking, conclusions as to the corrosion behaviour of a metal cannot be drawn from a different kind of corrosion attack. If an aluminium alloy shows itself, for example, resistant to attack by a sodium chloride solution, it can under

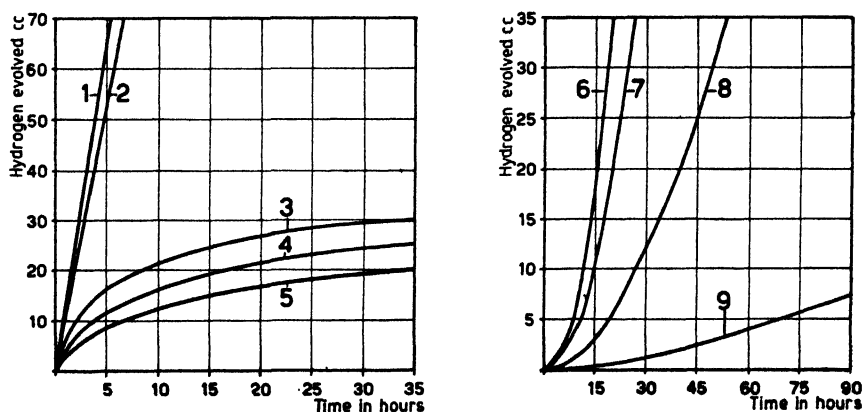


Fig. 82. Hydrogen evolution of various aluminium casting alloys.  
 left — in caustic soda solution. right — in 2% HCl.  
 1 Pure aluminium, 2 Silumin (CAI-Si) in 5% caustic soda. 3, 4, 5, Hy 11 (C Al-11Mg) in 10% caustic soda (3, heterogenised; 4, homogenised; 5, as chill-cast) 6 14% Mg 7 9% Mg. 8 8% Mg. 9 Pure aluminium.

certain conditions, fail with a solution of potassium chloride. It is necessary therefore that alloys under consideration for any application under corrosive conditions should be tested for corrosion resistance under the expected conditions of service. In such testing, simply raising the temperature will increase the rate of corrosion attack and thus will shorten the time of the test. An increase in the concentration of the corroding medium often has the opposite effect and reduces the rate of attack. Thus, for example, nitric acid of specific gravity 1.18 is the concentration giving strongest attack. When assessing the results of corrosion experiments, it must not be overlooked that under some conditions (passivating and protective

film formation) the rate of corrosion attack falls off with time, while the reverse is the case with surface roughening, when the attack increases with time, as shown in Fig. 82. Much experience is necessary for a reliable opinion in questions of corrosion to be given out of hand without extensive experiments.

TABLE 14

## SOLUTION POTENTIALS OF SOME METALS AND ALLOYS

Metal	Potential against normal calomel electrode in 2% air-saturated NaCl solution at 18-20°C, milliv., approx.	Potential against 99.3% pure aluminium in 2% air-saturated NaCl solution at 18-20°C, milliv., approx.
Magnesium . . . . .	—1600	— 850
Zinc . . . . .	—1050	— 300
C: Al-Zn-Cu . . . . .	— 850 to — 900	— 150 to — 100
Al-Mg and C: Al-Mg . . . . .	— 800 to — 850	— 100 to — 50
Al-Mg-Mn and C: Al-Mg-Mn . . . . .	— 760 to — 800	— 60 to 0
Al-Mg-Si and C: Al-Mg-Si . . . . .	— 740 to — 760	— 20 to + 10
Cadmium . . . . .	— 740 to — 760	— 20 to + 10
99.3% pure aluminium . . . . .	— 740 to — 750	0
Al-Si and C: Al-Si . . . . .	— 700 to — 730	+ 10 to + 50
Al-Cu and C: Al-Cu . . . . .	— 650	+ 100
Al-Cu-Ni and C: Al-Cu-Ni . . . . .	— 650	+ 100
Al-Cu-Mg (warm aged) . . . . .	— 650	+ 100
Al-Cu-Mg (aged at 20°C) . . . . .	— 580 to — 600	+ 150
Iron, mild steel . . . . .	— 600 to — 700	+ 50 to + 150
Lead . . . . .	— 480 to — 500	+ 250
Tin . . . . .	— 450 to — 470	+ 300
Brass (50% zinc) . . . . .	— 350	+ 400
Nickel . . . . .	— 270	+ 480
Brass (30% zinc) . . . . .	— 250	+ 500
Copper . . . . .	— 220 to — 250	+ 500
Silver . . . . .	— 50 to + 50	+ 700 to + 800
Mercury . . . . .	0	+ 750
Stainless steel . . . . .	+ 100	+ 850
Gold . . . . .	+ 220	+ 1000
Platinum . . . . .	+ 200 to + 350	+ 950 to + 1100

According to modern scientific views, corrosion can in most cases be attributed to galvanic action. For this reason a knowledge of the electrolytic solution potentials of the metals is of importance. Table 14 shows the solution potentials against the calomel electrode in the one case and against pure aluminium in the other as the electrode of reference, the more important of the heavy metals being included in the Table. If, for example, a steel angle is riveted to an Avional (Al-Cu-Mg) plate with steel rivets, as shown in Fig. 83, the steel with —0.65 volt is more electronegative than Avional with —0.60 and is anodic, i.e., it tends to be dissolved, while Avional is galvanically protected. On the other Avional warm aged at 80°C (176°F) with a potential of —0.72 volt is electronegative to mild steel,

and in this case it becomes anodic and is attacked. Although Anticorodal (Al-Si-Mg) is more resistant to sea water than Avional, its behaviour under the above conditions is similar to that of warm-aged Avional in consequence of its solution potential of  $-0.75$  volt.

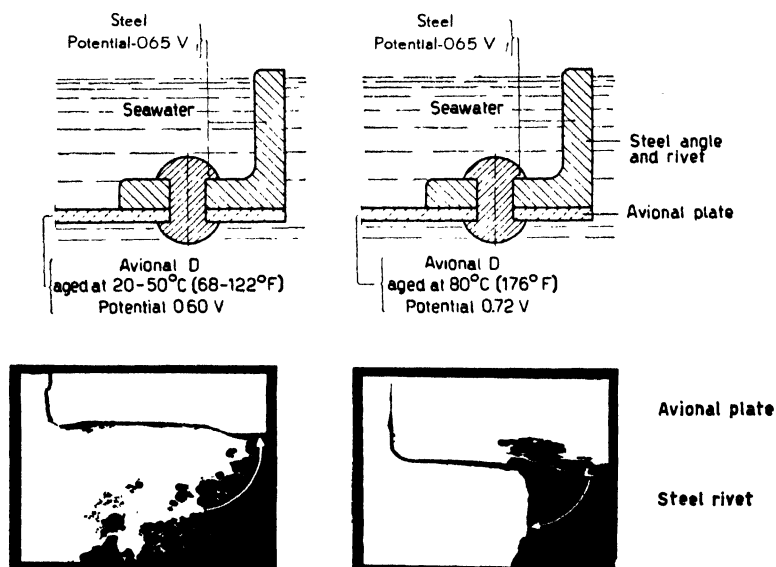


Fig. 83. Local galvanic action between Avional (Al-Cu-Mg alloy) and steel.

Left: Potential difference between steel and Avional D =  $-0.65 - (-0.60) = -0.05$  volt.  
Steel attacked and Avional protected galvanically.

Right: Potential difference between steel and Avional D =  $-0.65 - (-0.72) = +0.07$  volt.  
Avional attacked and steel protected galvanically.

For control purposes in the manufacture of some aluminium alloys, the MYLIUS thermic hydrochloric acid test is used. In this, a test piece 20 sq.cm in surface area is cleaned by pickling and placed in an externally insulated corrosion beaker with a thermometer together with 20cc of exactly 10% HCl at  $20^{\circ}\text{C}$ , and is so subjected to chemical attack under these standard conditions. The heat of reaction causes the temperature of the HCl, to rise towards a limiting value and the mean rate of temperature rise per minute up to the maximum temperature serves as the measure of corrosion.

$$\text{Reaction number (MYLIUS)} = \frac{\text{Rise of temperature } ^{\circ}\text{C}}{\text{Time in minutes}}$$

With highly corrosion-resistant alloys there is only a small increase of temperature which is not easy to observe accurately. In such cases the

hydrogen evolution is used as a basis for determining the reaction number according to the following formula,

$$\text{Reaction number} = \frac{\text{Volume of H}_2 \text{ evolved in cc}}{\text{Time in hours} \times \text{surface in sq.cm}}$$

b. *Intercrystalline corrosion*

Intercrystalline corrosion already referred to, is a matter which requires special attention. It has been found that a solution of 30 gm NaCl and 10 gm HCl per litre is particularly suitable for the detection of any tendency to intercrystalline corrosion in the Al-Cu-Mg alloys. A metal test specimen of 10 sq.cms surface area is subjected to corrosion attack for 2 hours. If the evolution of hydrogen amounts to less than 1 cc, the alloy is not susceptible to intercrystalline corrosion. If the hydrogen is 1 to 3 cc there

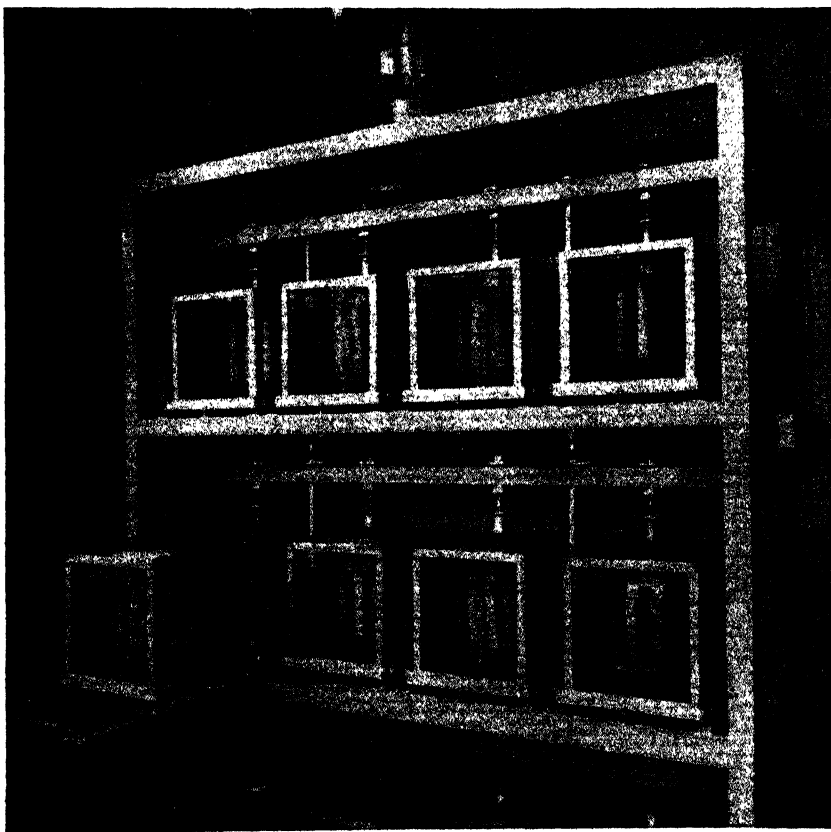


Fig. 84. DVL stirring frame for accelerated corrosion tests.

is a small susceptibility to intercrystalline corrosion and if over 3 cc a strong tendency thereto.

Another corrosion test for the same purpose is carried on in a stirring apparatus of 10 litres capacity in which the test specimens, as shown in

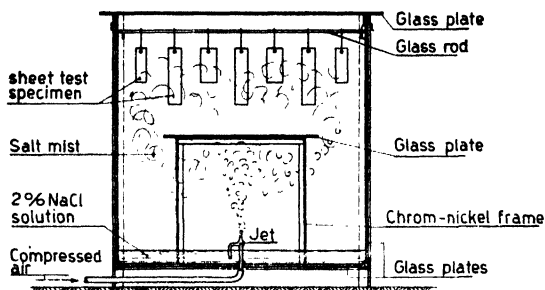


Fig. 85. Salt spray cabinet for corrosion tests in salt mist.

A similar stirring apparatus (DVL) with a corroding liquid containing 0.1% of  $H_2O_2$  and 3% NaCl at 20°C is used for the determination of general corrosion. The duration of the test is up to 4 months and specimens are taken out at predetermined intervals such as  $\frac{1}{2}$ , 1, 2, 3 and 4 months and are at once tested in tensile to record the progress of the corrosion attack. To eliminate the effect of cut edges, the corroded test pieces are individually milled to shape prior to the tensile test.

### c. Salt spray test

The salt spray test (Fig. 85) is used to estimate the resistance of the material to exposure to the weather under coastal conditions. This test is carried out in a salt spray cabinet of about 3 feet cube, into which is air-sprayed 2 litres of a 3% NaCl solution every day. In general these air-spraying are carried out intermittently, say for 15 minutes every 2 hours. As in the DVL test, a large number of similar specimens are submitted to

Fig. 84, are secured in bakelite frames spaced 1 inch from the wall of the vessel, while a stirrer running at 135 r.p.m. keeps the corroding liquid (1% HCl plus 3% NaCl solution) in motion. The duration of the test is from 1 to 3 days and the extent of the corrosion attack is determined by the loss of strength and of elongation.

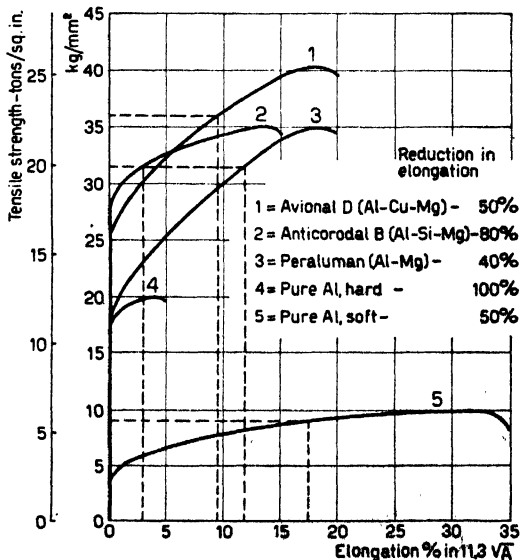


Fig. 86. Effect of exposure to corrosive conditions on tensile strength and elongations of various aluminium alloys.

the test at the same time and they are taken out for tensile testing from time to time. In order to obtain a true comparison of the corrosion resistances, it is advisable that specimens of the various alloys or other metals to be compared are subjected to the test at the same time. The salt spray test has an effect about 50 times faster than the action of the weather in Switzerland even in the least favourable climatic conditions in that country.

As can be seen from Fig. 86, the effect of corrosion on elongation is considerably greater than the effect on tensile strength. In the case of soft tempered pure aluminium, the drop in strength is from 6.3 to 5.7 tons/sq. in. (14000 to 12800 lb./sq. in.), while the drop in elongation is from 35 to 17.5%. In the case of Avional the tensile strength drops from 25.4 to 22.9 tons/sq. in. (57000 to 51000 lb./sq. in.) and the elongation from 20 to 10%.

#### d. Stress corrosion

It is found that the rate of corrosion, especially intercrystalline corrosion, is increased by mechanical stress. It is therefore desirable to carry out stress corrosion tests in which specimens are subjected to corrosion under load. This is done, as shown in Fig. 87, with the specimens loaded mechanically under a calculated bending stress, either by suitably fixing them in wood frames or by loading with weights. The so called loop test is also frequently used in which the specimen is stressed within the elastic limit by being bent round and its ends riveted together. Such specimens can be subjected to corrosion attack in the salt spray cabinet or in any required liquid

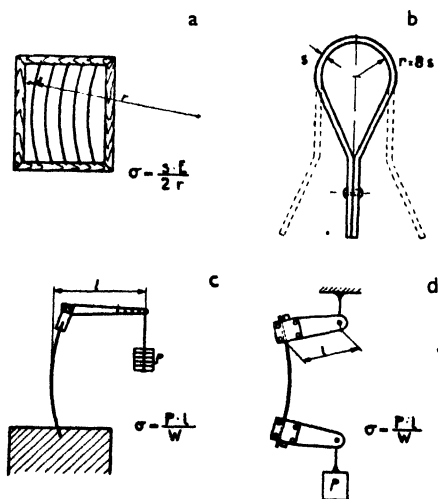


Fig. 87. Different forms of stress-corrosion tests.

a) frame test. b) loop test. c) and d) weight loading. ( $W = \frac{2l}{3}$ )



medium, the time to fracture being taken as the measure of the corrosion resistance.

For tests on intercrystalline corrosion, a minimum time to fracture of the loop of 100 days in a solution of 3% NaCl and 1% HCl is prescribed.

### 3. ANALYSIS

#### a. Chemical analysis

In finding the purity of aluminium, it is not the aluminium content that is determined, but that of the different impurities, the aluminium content being calculated by difference. This method is necessitated by the fact that an exact determination of the aluminium content, if this preponderates in the alloy, cannot be made with the required accuracy. The principal impurities in virgin aluminium are Fe, Si, Cu, Zn and Ti. In secondary aluminium, all metals may be present in varying proportions. The accurate analysis of aluminium requires considerable experience and can therefore only be carried out reliably by trained chemists. Standard methods of analysis have been compiled by the Bureau International des Applications de l'Aluminium, Paris, under the title of "Approved methods of analysis for aluminium and its more important alloys", also by the Aluminium-Zentrale. In addition, methods are in use for the determination of carbon, sodium and aluminium oxide in aluminium.

#### b. Spectrochemical analysis

In recent years, spectrographic analysis is being used to an increasing extent for the assaying of aluminium and its alloys. The great advantage of the spectrograph is that all impurities are immediately revealed even though not of regular occurrence, whereas with chemical analysis, only the metals sought by the special methods adopted are determined. Furthermore there exists, in the spectrum photograph (Fig. 88), a document available at any time for subsequent reference. Again it is very much cheaper and quicker to carry out a spectrographic analysis than a chemical analysis.

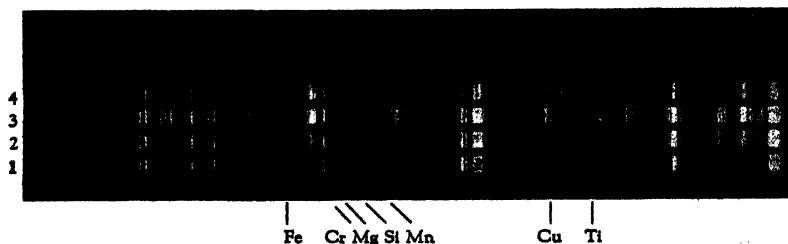


Fig. 88. Spectra of various aluminium alloys.

- |    |           |          |           |           |          |           |          |  |  |
|----|-----------|----------|-----------|-----------|----------|-----------|----------|--|--|
| 1) | 0.06% Si, | 0.06 Fe, | 0.004 Cu, |           |          |           |          |  |  |
| 2) | 0.20% Si, | 0.28 Fe, | 0.032 Cu, | 0.022 Ti, | 0.11 Cr, | 0.026 Mn, | 0.10 Mg, |  |  |
| 3) | 1.18% Si, | 0.69 Fe, | 0.13 Cu,  | 0.12 Ti,  | 0.10 Cr, | 0.82 Mn,  | 0.50 Mg, |  |  |
| 4) | 0.64% Si, | 0.79 Fe, | 4.00 Cu,  | 0.11 Ti,  |          | 0.52 Mn,  | 0.81 Mg, |  |  |

An essential prerequisite is the availability of standard samples of perfect accuracy, such for instance as those supplied by the Aluminium-Industrie A.G. In the usual method of spectrographic analysis, reference specimens of known composition are always used as controls, and the contents of the various elements are estimated by comparison of the intensity of the corresponding lines photometrically. Quite recently methods have been developed to dispense with the sparking of standard samples for each plate or film and in these the photographic characteristic of the emulsion batch used must be determined beforehand. By the use of films instead of plates, the carrying out of a spectrographic analysis can be so much shortened that from the insertion of the sparking sample to the reporting of the result there is a time interval of only 12 to 15 minutes, and it is then not impracticable to hold up the casting of metal until the spectro-analysis has shown the composition to be correct. In the case of some alloy constituents, such as copper, spectro-chemical analysis is unsuitable for the higher metal contents, and chemical analysis must generally still be used in such cases. The apparatus required for spectrographic analysis is illustrated in Fig. 89, and includes the following items:

- a: Feussner spark generator
- b: Time switch
- c: Revolving multiple spark stand for adjusting of specimen, presparking, and test sparking

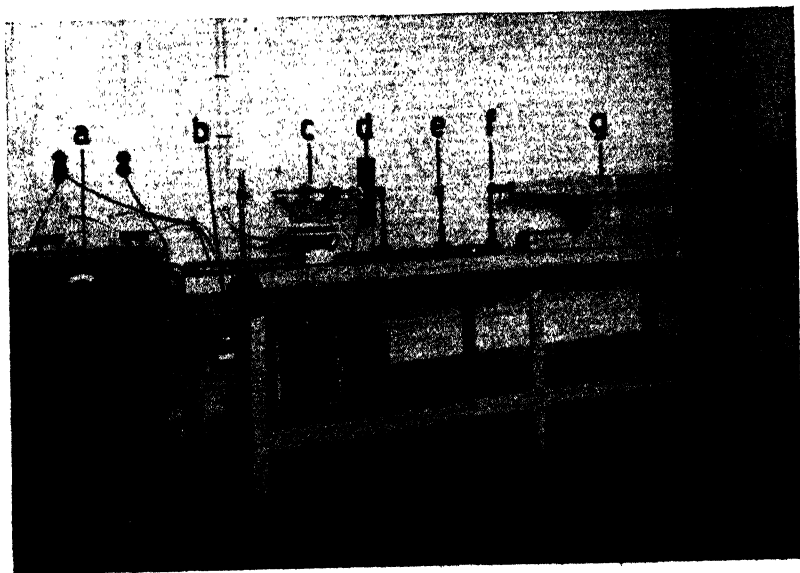


Fig. 89. Analytical spectrograph.

d: Mercury lamp for the ionisation of the spark gap

e: Slit

f: Shutter

g: Spectrograph

h: Plate holder

A method of spectrochemical analyses was developed by HASLER and DIETERT in America during the recent War, in which, by means of 12 photoelectric cells, the intensity of selected spectrum lines of elements to be determined is read directly. With this method it is possible, without further complication, to read off the contents of the alloying elements at the time of sparking the test pencils. At the same time the advantage is lost of having the spectrum photograph as a permanent record available for inspection at any subsequent time.



Fig. 90. Reagent case for spot tests.

#### c. Spot tests

In fabrication and particularly in repair work, it is often of importance to confirm qualitatively the type of alloy in cases of uncertainty. In welding jobs, this may be necessary for instance, in order to be able to select the correct filler rod, or in the case of an assembly with other

unknown parts, in order to be able to use an alloy of similar electrochemical potential. Fig. 90 illustrates a case fitted with the necessary apparatus and reagents for these tests.

#### *Procedure for spot testing*

Should an aluminium alloy of unknown composition have to be tested, the alloy type may be readily determined by the following sequence of tests. If on the other hand it is only required to determine to which of two known types in question it belongs, only that constituent is tested for, that may be different in the two alloys.

##### (i) *Caustic soda test*

The surface of the metal is rubbed clean with emery paper and 1 or 2 spots of 20% caustic soda solution are placed on it and allowed to act

for about 5 minutes. When the spot is washed off with water, alloys containing copper, nickel and zinc, singly or collectively show a distinct blackening at the spot that was wetted with the solution. Alloys with over 2% of silicon show a grey-brown colour at the spot which is more distinctive the higher the silicon content. Other alloys and pure aluminium are etched white by the solution. Pure magnesium and magnesium alloys are not attacked by the solution.

(ii) *Nitric acid test*

If there was a black or brown spot in Test (i), a drop of concentrated nitric acid is placed with a glass rod on the dark spot after it has been dried with filter paper. The blackening is removed instantly if it is due to copper, nickel or zinc, but the dark colour persists if it is due to a silicon-rich alloy. Pure magnesium and magnesium alloys are vigorously attacked.

(iii) *Ammonia test (confirmatory for copper)*

The spot treated with nitric acid (Test (ii)) is made alkaline with 1 or 2 drops of strong ammonia, (the alkalinity being confirmed by smell or by testing with red litmus paper) the liquids being allowed to run together at the end of a slightly inclined glass rod. A blue colouration in the liquid, readily perceptible in this way, indicates copper. In doubtful cases a check is made with Test (iv) below.

(iv) *Alkali ferrocyanide test (more sensitive confirmatory test for copper)*

A drop of the ammoniacal liquid from Test (iii) is picked up on a glass rod and touched on ferrocyanide paper (filter paper soaked in alkali ferrocyanide solution and dried). When small traces of copper are present, the drop will dry out to a rosy red spot. If a blue spot is produced when the liquid is placed on the alkali ferrocyanide paper, the liquid was not alkaline and the test must be repeated after the addition of a further drop of ammonia.

(v) *Dimethylglyoxime test (confirmatory for nickel)*

If Test (i) gave a dark colouration, which disappeared in Test (ii), the alloy may contain nickel. To confirm this element, Tests (i) and (ii) are repeated, the nitric acid drop is transferred to nickel reagent paper (soaked with 1% alcoholic dimethylglyoxime and dried), and a drop of strong ammonia is added to the moist spot. The appearance of reddening indicates nickel.

(vi) *Manganese confirmatory test*

For testing manganese, the surface of the metal is touched with a drop of caustic soda solution as in Test (i). When the reaction is completed, and without rinsing off the spot, sufficient concentrated nitric acid is added until any precipitate formed is substantially all redissolved (a test with blue litmus paper must show an acid reaction). Then a few particles of sodium bismuthate are added and stirred in to the nitric acid solution with a glass rod. When manganese is present, the liquid acquires the wine-red colour of permanganate due to the oxidation of the manganese. The oxidation of the manganese can also be brought about with ammonium persulphate in the presence of silver nitrate as a catalyst. Since this oxidation only proceeds at an elevated temperature and in addition as this test calls for the use of a further reagent (silver nitrate solution) the sodium bismuthate method already described is preferred.

(vii) *Cadmium sulphate test*

On to the surface of the metal rubbed clean with emery paper is placed a drop of a solution containing 5% cadmium sulphate, 5% nitric acid and 3% common salt. On alloys which are less noble than cadmium, there is immediately formed at the spot, a greyish black deposit of sponge cadmium. Among such less noble alloys belong the following types of alloys Al-Zn, Al-Zn-Mg, Al-Zn-Cu, and Al-Mg. Also magnesium and its alloys are less noble than cadmium. With pure aluminium and alloys of the type Al-Mg-Mn, Al-Mg-Si, and Al-Mn, which have a similar potential to cadmium, the cadmium sulphate solution only gives a weak reaction, and the more noble alloys of types Al-Cu, Al-Cu-Mg and Al-Cu-Ni, are generally not appreciably attacked by this reagent.

(viii) *Magnesium confirmatory test*

From the piece to be tested for magnesium, a small quantity of filings (2 to 3 milligrammes) are removed by means of a clean file. These are completely dissolved in a small test tube with about 5 drops of concentrated HCl and the clear solution is diluted with 1 to 2 cc of distilled water. Copper-containing alloys are dissolved in dilute HCl (5 drops distilled  $H_2O$  + 5 drops concentrated HCl) and the undissolved residue of sponge copper filtered off in a small filter and the filtrate diluted similarly with distilled water. To the dilute HCl solution is added 2 to 3 drops of a very dilute solution of 1-, 2-, 3-, 5-, 8- tetraoxyanthraquinone in caustic soda solution and a few small particles of aluminium powder, or even a few

filings of the same alloy. Then as much 20% caustic soda solution is added as is necessary to turn the red colour of the reagent (acid) to blue-violet (alkaline). When magnesium is present it forms a cornflower blue precipitate at this stage. If the alloy has only a low content of magnesium, a distinctly visible blue precipitate is only formed on heating the solution. It is important for the success of this test that too much of the intensive colouring reagent is not added, as an excess of the dyestuff makes more difficult the recognition of the blue precipitate.

Correct measurement of the tetraoxanthraquinone addition ensures that the dyestuff is used up in the formation of the blue colouring matter, so that on heating, the liquid becomes colourless or nearly so, while the flocculent precipitate is coloured blue. If the alloy is magnesium-free, the transparent blue-violet colour of the solution is formed after even the smallest addition of the dyestuff. With Al-Mn alloys a precipitate forms in the blue-violet solution after the addition of caustic soda solution and heating, but it is possible to see clearly by transmitted light against a white background that it is not blue.

#### (ix) Solubility test (Si confirmation)

As much aluminium filings from the alloy to be tested as will go on a penknife blade are added in small quantities to about 3 cc of dilute HCl — HNO<sub>3</sub> solution. If the alloy does not contain over 1% of silicon, the filings are completely dissolved in the acid, which remains clear. With a silicon content of about 2%, a dark grey turbidity is formed, which deepens as the Si content increases. With high silicon contents (e.g. Silumin), a grey black precipitate is formed.

### 4. MACRO- AND MICROSCOPIC EXAMINATION

#### a. Macroscopic examination

Of chief interest is the determination of the grain-size of wrought material that is to be further worked. This is rendered visible by etching the bright metal surface, a suitable etching reagent being composed of:

- 20 cc concentrated HCl (38%)
- 20 cc concentrated HNO<sub>3</sub> (65%)
- 5 cc concentrated HF (30%)
- 20 to 40 cc water.

For alloys which are rapidly attacked, the etching solution is diluted with a greater proportion of water.

For bringing up surface defects on sheets, a 10%  $\text{H}_2\text{SO}_4$  solution used at 50°C is suitable.

For foil, the following etching reagent answers the purpose: 100 cc of 5% aqueous  $\text{FeCl}_3$  solution, and 5 to 8 drops of concentrated HF.

#### b. Microscopic examination

For examination of the microstructure of aluminium alloys, it is generally necessary to work with rather high magnifications, from 50 to 1500 diameters. The surface of the specimen must be flat and perfectly polished. In the polishing process, the surface to be examined is cut smooth by turning or milling. The surface is then ground beginning with coarse emery paper, 1 F, and passing in turn to successively finer papers 2/0, 4/0 to 6/0, the direction of polishing being turned through 90° in passing from one paper to the next finer. It is of assistance to lightly impregnate the paper with paraffin.

The final polishing of the rough polished surface is then done on a revolving polishing wheel on which is stretched a polishing cloth moistened with 2% aqueous soap solution with an addition of alcohol. For the polishing medium, alumina is used to commence with, and levigated magnesia for the final polish. Recently, electrolytic polishing is used (as developed

for instance by JACQUET), particularly for Raffinal or super purity aluminium. In this method, 1 part of perchloric acid (sp. gr. 1.48 at 20°C) and 3.6 parts acetic anhydride are used as electrolyte, the current density being 4 to 8 ampères per sq. decimetre at 18 to 25°C. This process must be carried out with caution as it is apt to be explosive. It is not suitable for impure metal nor for alloys on account of the selectivity of the etch.

The alloy constituents

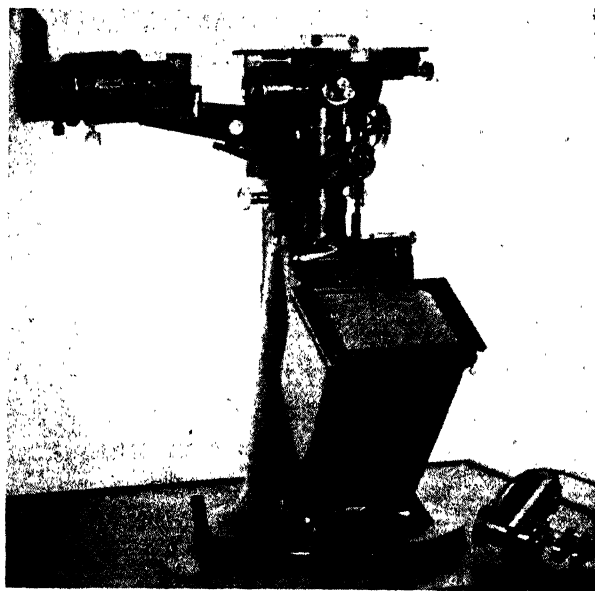


Fig. 91.

Modern metallurgical microscope (Busch, „Metaphot”).

are rendered visible on the highly polished surface by use of the following etching reagent :

1. For the development of the alloy constituents:  
10 drops HF 30%  
10 drops concentrated  $\text{HNO}_3$   
100 cc distilled water  
Etching time 15 to 60 seconds
2. For the development of grain boundaries:

For Al-Cu-Mg alloys, pure and super purity aluminium:

- 1 cc HF (about 30%)  
1.5 cc concentrated HCl  
2.5 cc concentrated  $\text{HNO}_3$   
95 cc distilled water

Time of etch —

Al-Cu-Mg alloy  $\frac{1}{2}$  to 1 minute

Pure aluminium 3 to 5 minutes

Super purity aluminium 10 to 15 minutes

For Al-Mg-Si wrought alloys :

100 cc 5% aqueous  $\text{FeCl}_3$  solution

15 to 20 drops HF

Time of etch — 2 to 4 minutes

For Al-Mg alloys :

100 cc 9% aqueous phosphoric acid

Time of etch — 20 to 30 minutes.

A metallurgical microscope is used for the examination of the surfaces of the specimens. Instead of the optical bench in general use at one time, there are today much more compact instruments available, as in Fig. 91. In these the specimen can be observed

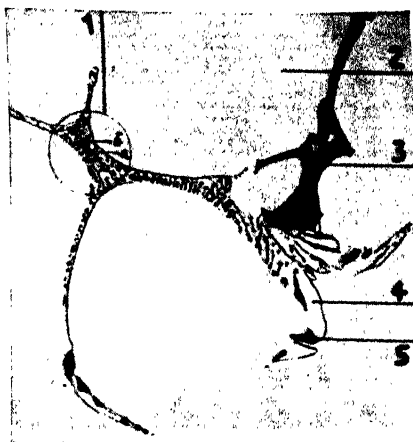


Fig. 92.

Microstructure of Avional (Duralumin Al-Cu-Mg) etched with HF +  $\text{HNO}_3$ ,  $\times 500$ .

1. Ternary eutectic Al + Cu  $\text{Al}_2$  + Mg<sub>2</sub> Si.
2. Al-Cu-Mg solid solution.
3. Ternary phase Al-Mn-Cu.
4. Cu  $\text{Al}_2$ .
5. Mg<sub>2</sub> Si.

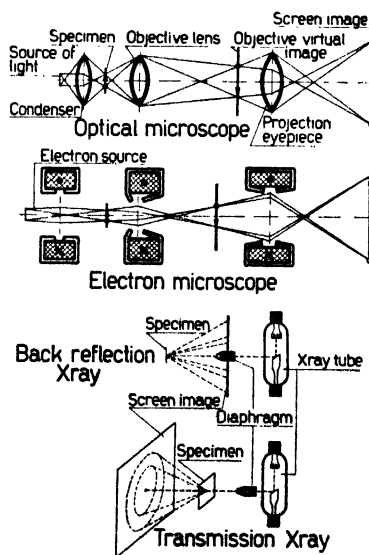


Fig. 93. Paths of rays in optical and electron microscopes and in X-ray diffraction photography.





Fig. 94.

Electron microscope — Trüb, Täuber & Co. A. G., Zürich, Switzerland.

and transmission methods (Fig. 93). With X-ray diffraction examination, the processes of precipitation hardening and recrystallisation, and the crystal orientation, for example, can be made visible, which could not be

by eye or can be projected on a ground glass screen or photographic plate. Fig. 92 shows a section of Avional (Duralumin, Al-Cu-Mg) at 500 magnification on which can be clearly seen the different constituents in this complex alloy.

Naturally considerable experience is necessary to interpret such structures correctly. The wavelength of light limits the magnification to a maximum of 3000. The recently developed electron microscope permits much greater magnifications of up to 80000 diameters. The similarity in the refraction in the optical microscope and the electron microscope is shown in Fig. 93. At the side are shown a photomicrograph from the optical microscope and a pure aluminium specimen under the electron microscope at 20000 diameters. Fig. 94 illustrates the latest type of electron microscope by Trüb-Taüber & Co., Zürich.

For the examination of the crystal texture of a metal, we must use the help of X-rays. The methods principally used are the back reflection

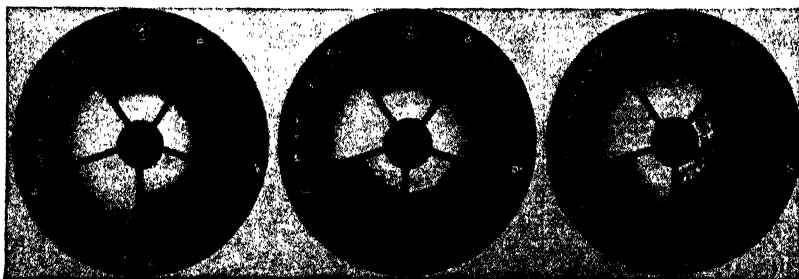


Fig. 95. X-ray diffraction photographs of different fractures in Al-Zn-Mg alloys (for identification see text).

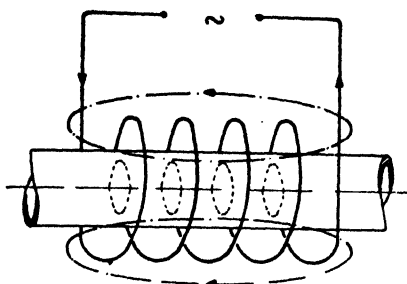


Fig. 96.

Diagrammatic illustration of principle of Periflux apparatus for tube testing (Industrial Sheet, 1942).

observed previously. The possibilities opened up by structural investigations of metallurgical processes are illustrated in Fig. 95, showing X-ray diffraction photographs of the following types of fracture:

- a: static tensile
- b: fatigue bending
- c: static reversed bend
- d: static combined tensile and bend
- e: notched bar impact.

In composite picture (1), the exposure was made directly on the surface of the fracture, in (2) 1 mm below the surface and in (3) 10 mm below. A comparison of the three pictures shows the possibility of drawing subsequent conclusions of the cause of fracture from X-ray photographs.

## 5. NON-DESTRUCTIVE TESTING

In recent times some very interesting non-destructive electro-physical tests for materials have been developed. These depend on the effect of

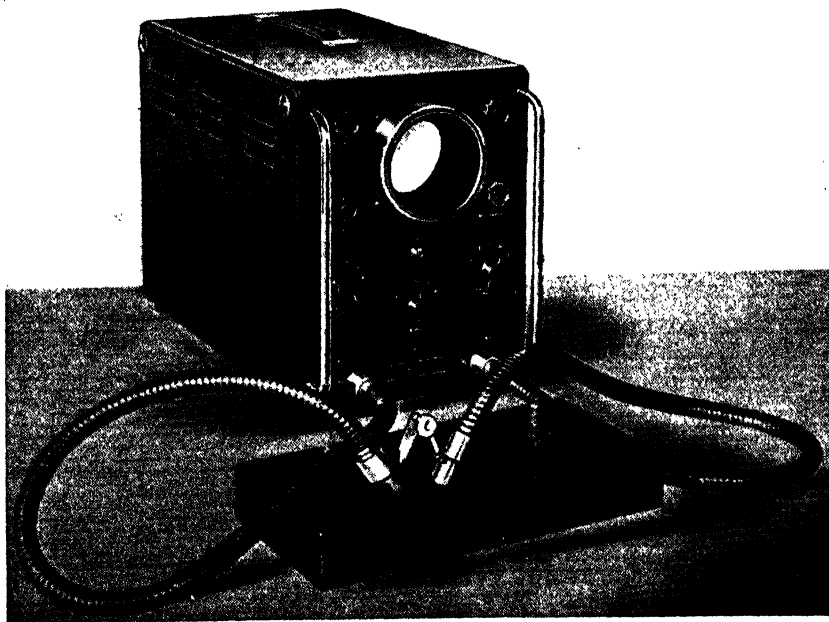


Fig. 97. Ultrasonic flaw testing apparatus — (Henry Hughes & Son Ltd.).

electrical oscillations through the light metal, mainly on the eddy current principle, as shown in Fig. 96 for the testing of tubes. By means of a bridge and an appropriate coil, the wall thickness of tubes, torn surfaces and other metal defects in semifabricated light metal, and also the hardness, thickness of oxide coating such as an anodic coating, or coatings of lacquer or plated coatings as well as the composition of the alloy and its heat-treatment can be examined. The testing and comparison of wall thickness and surface defects in tubes, rods and strips, can even be developed to a certain extent as an automatic continuous method. In Fig. 97 is shown a testing apparatus as developed by Henry Hughes & Son Ltd., with which bar stock can be examined as desired for tears, double metal, slivers, blisters, heat-treatment, alloy type and dimension.

## CHAPTER IV : DESIGN AND CONSTRUCTION

### 1. PRINCIPLES OF DESIGN AND CONSTRUCTION

Considering the technical and economic characteristics of aluminium, its outstanding advantages lie in its low specific gravity combined with high strength, its ease of working, good forming qualities in forging and pressing, and its high scrap value. On the contra side are its somewhat high price, its low modulus of elasticity, its notch sensitivity, the need or at least the preferability of special machines for working it, and its susceptibility to surface damage.

The designer who has been accustomed to working only with heavy metals does best to learn to think in terms of the light metals. One of his main objects must be to increase the moment of inertia in order to improve the stiffness of the light metal structure while retaining a minimum volume, and he must bear in mind the almost limitless possibilities in the shapes of sections obtainable by extrusion.

It is common experience to encounter light alloy structures in which the same design and method of construction as were used for heavy metal are retained, the iron or steel merely having been replaced by light metal. The optimum saving in weight is never obtained by this procedure.

In changing from iron and steel to light alloy construction in the workshop, there is sometimes some difficulty in introducing the necessary new ideas to the workpeople, from the supervisors down to the labourers, as these people generally work on the supposition that the old established methods of iron work apply also to light metal work, which however is certainly not always the case. Therefore it is necessary that the understanding and appreciation of the characteristics and peculiarities of light

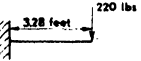

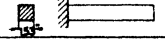
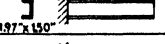

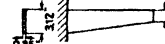

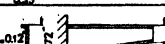
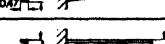
Loading conditions 				
No	Type of cantilever	Wgt of cantilever Lbs	%	
1		29.9	100	
2		26.4	88	
3		12.7	41	
4		12.9	43	
5		9.6	32	
6		8.8	29	
7		5.5	18	
8		3.7	12.5	

Fig. 98. Weights of cantilevers of various form and of equal maximum load-carrying capacity (after W. Kloth).

metals should be inculcated in the organisation. A typical example of this is the customary centre punching and scribing of bends. Owing to the notch sensitivity of light alloys, marks made by scribes or centre punches are to be regarded as dangerous starting points of fracture.

We can distinguish two main factors of progress in modern engineering design, namely lightness of form and lightness of material. It is a strange thing that the former came into being through the latter, just as in general the developments in heavy metal technology in recent years have always made progress through the advances in light alloys.

The principles of light metal constructional methods are illustrated in Fig. 98, which also shows the difference between the light and heavy metals.

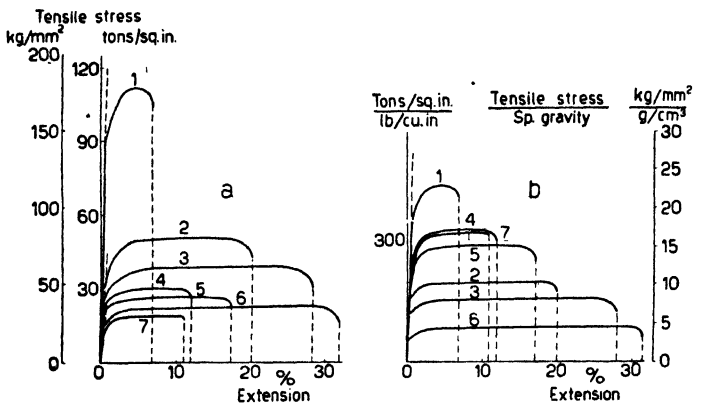


Fig. 99. Stress-strain curves for aircraft materials.

- |   |                                  |
|---|----------------------------------|
| 1 Stainless Cr-Steel.                     | 5 Duralumin 681 B.               |
| 2 0.6 C steel.                            | 6 0.11 C, 0.48 Mn welding steel. |
| 3 0.35 C, 0.53 Mn, 0.43 Si welding steel. | 7 Electron AZM.                  |
| 4 Duralumin 681 ZB.                       |                                  |

Comparing the strength of the standard aluminium alloys with those of steel (Fig. 99) we find about the same proof stress with however an appreciably higher tensile strength for steel. The true picture is, however, only given by the specific strength, in which only the high tensile steel exceeds the Al-Cu-Mg alloy.

Since in every structure some members are loaded in bending or compression, in which conditions the modulus of elasticity is an important factor, an increase of section for light alloy when replacing heavy metal construction is essential. Comparing the tensile strength of chrome steel at 76 tons/sq.in. (170000 lb./sq. in) and a proof stress of 63 tons/sq. in (140000 lb./sq. in) with that of the Al-Cu-Mg alloy with 28 tons/sq. in (63000 lb./sq. in) tensile and 20 tons/sq. in (45000 lb./sq. in) proof stress, it can be shown that, in regard to bending, owing to the greater degree of slenderness with the highest strength chrome steel, in certain conditions there may be equivalence in weight between even this steel and aluminium.

This indicates also that steel should preferably not be chosen for thin walled structures owing to the danger of buckling.

In replacing steel by light alloy, it is possible to make use of sections having greater moments of inertia without fear of buckling, since the cross sectional area is greater than with steel beams. The use of light alloy is more favourable from the standpoint of lightness in the case of beams than of struts, if restriction of space does not compel the designer

to use sections of only small moments of inertia. In torsion it is likewise to be noted that the polar moment of inertia increases as the cube of the diameter, while the weight increases only as the square, so that for this condition the specifically lightest metal magnesium has the advantage.

Comparing a structural steel having a proof stress of about 25 tons/sq. in. (56000 lb/sq. in.) with Avional with about 20 tons/sq. in. (45000 lb/sq. in.) proof stress, it can be seen from Fig. 100 that the following weight saving is possible with the use of Avional; with tensile loading 53%, with bending loading with a similar factor of safety 59%, while on the other hand with equal deflection in bending the saving is only 34%, and as a strut 48%.

Fig. 101 shows the difference in section of a connecting rod using steel in one case and light alloy in the other. To achieve the greatest saving in weight an increase in moment of inertia must be aimed at, in accordance with the principles of light alloy design, and thanks to the good forming properties of aluminium alloys, a much smaller thickness of section can be realised than with the heavy metal by forging or pressing

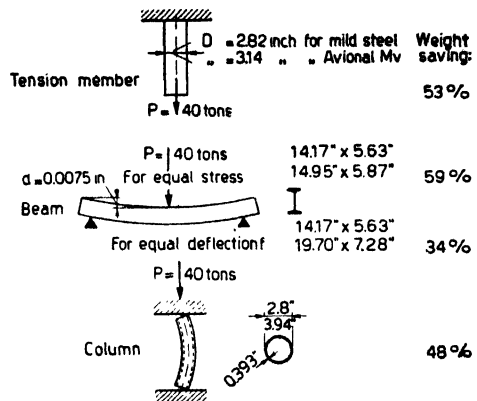


Fig. 100. Comparison of weight saving with Avional (Al-Cu-Mg, Duralumin) against mild steel in different structural members.

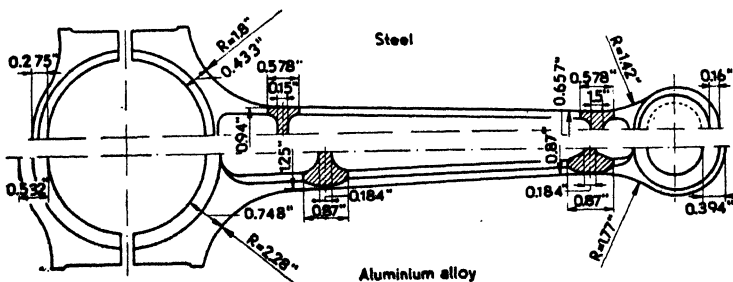


Fig. 101. Connecting rod in steel and in light alloy showing effect of Young's modulus on profile.

to size, as a result of which subsequent machining can be reduced to a minimum. A considerable offset to the higher metal cost results from the smaller machining costs, and in the most favourable cases, light alloy construction may be even cheaper than execution in steel, this being so particularly in large lots in which the provision of special tooling arrangements is justified.

## 2. FORMING TO SHAPE

The light metals can be given shape by a great variety of methods. In casting, the sand casting, gravity die casting, pressure die casting and cold chamber die casting or press casting processes may be used, and in consequence of the low casting temperature, the metal moulds have a long life which increases the economy of the methods in which they are employed. Die casting is specially advantageous, as due to the rapid and fine grained solidification, castings made by this process have a higher strength than sand castings and additional advantages of closer dimensional accuracy and superior surface quality. Mechanical forming processes applicable to the light metals comprise rolling, section and tube extrusion, forging, pressing, metal spinning, drawing and bending. Owing to its crystal structure (face-centred cube lattice), aluminium is very much easier to work mechanically than magnesium (hexagonal lattice), which can only be satisfactorily wrought at elevated temperatures. Wrought material possesses

TABLE 15  
PRESSURE REQUIRED IN FORGING AND PRESSING

Alloy Type	Particular alloy	Forging Temperature		Pressure for 50% reduction		% reduction under drop stamp	
		°C	°F	Tons/sq. in	1000 lb. sq. in	%	
—	Pure aluminium	525	977	0.6	1.3	33	1
Al-Si-Mg	Anticorodal, BA25	480	896	1.5	3.4	18	0.6
—	Brass	700	1292	1.5	3.4	17	0.55
Al-Cu	25S (U.S.A.)	450	842	2.2	4.9	—	—
Al-Cu-Mg	Avional						
—	Duralumin	420	788	2.5	5.6	10	0.3
—	Mild Steel	1000	1832	2.8	6.3	10	0.3
Al-Cu-Mg	Superalumin,						
—	DTD 390	420	788	2.9	6.5	—	—
Al-Mg-Mn	Peraluman 2, BA21	410	770	3.0	6.7	—	—
Al-Mg	Peraluman 7, MG7	430	806	3.8	7.8	—	—
—	Pure magnesium	460	860	1.1	2.4	—	—
Mg-6Al	Aviomag K6,						
—	Elektron AZM	370	698	4.1	9.2	11	0.33
Mg-2Mn	Aviomag Am						
—	Elektron AM 503	460	860	1.9	4.3	23	0.7

much greater uniformity of structure and higher strength than cast material, so that for highly stressed parts, forming by mechanical working is to be preferred. In the case of heat-treated alloys, a small amount of mechanical deformation may be applied immediately after heat-treatment whereby the proof stress is increased. Table 15 gives the resistance to working of the different light alloys in comparison with cast iron and brass.

### 3. METHODS OF ASSEMBLY

Light metals can be joined by oxy-acetylene or electric welding, soldering, riveting, screwing, by folded seams and by the use of a thermo-setting plastic cement. In soldering and welding it is to be particularly noted that heat-treated or work-hardened materials become softened by the soldering or welding process and undergo a considerable local loss of strength. However, when alloys of the Al-Mg type are welded in the soft condition in which they have a fairly high strength due to their magnesium content, no loss of strength occurs through the welding heat. In other cases, it is advantageous that the welded seam is located in a position of reduced stress, so that a loss of strength has a less adverse effect. It must also be remembered that with the heat-treated alloys, a heterogeneous precipitation takes place on heating, which results in a diminution of corrosion resistance in the heated area. Of the magnesium base alloys, only the Mg-2Mn can be satisfactorily welded, and this is one reason why this alloy is largely used for sheets. Due to the above complications in welding, the most widely used method of joining the heat-treated alloys is riveting, which is used very extensively especially in aircraft. Since light alloy rivets are driven cold, they exert no tightening effect, and transfer of stress is due solely to bearing pressure and shear stress. For this reason, accurate drilling of the rivet holes is essential. Owing to their greater resistance to heading more powerful riveting tools are required for light metal rivets than for steel, the maximum shank diameter of light alloy rivet that can be driven by hand being 16 mm or 11/16 inch. For riveting magnesium alloy parts, Al-Mg alloy rivets are generally used. At joints subjected to fluctuating loads, it is found that a coat of tough varnish between the surfaces to be joined is an advantage. This prevents frictional oxidation and improves the fatigue resistance of the joint.

Screws should only be manufactured by the thread rolling or pressing process in small sizes, and above  $\frac{1}{8}$ " diameter should always be produced in screw cutting machines. A suitable lubricant for driving screws consists of a mixture of neat's-foot oil and flocculated graphite. Light alloy screws or nuts are not suitable for applications requiring frequent turning, and in such cases bushing of the part with heavy metal to take the screw thread is recommended.



A very recent development in jointing aluminium and its alloys, is the adoption of plastic cemented joints using a synthetic resin adhesive.\* The plastic used polymerises at 150 to 200°C (302-392°F) in a very brief time and gives joints of extraordinary strength. This process has been used in America and England in aircraft construction and will undoubtedly find increasing application in manufacture.

In duplex structures composed of both heavy and light metal, the different coefficients of thermal expansion must be taken into account, the coefficient for light metal being twice as great as for iron. For a change in temperature of 10°C (18°F) there is developed a stress of about 1.3 tons/sq. in. (2900 lb./sq. in.) between members of iron and aluminium joined firmly together. In bimetallic structures there is a risk of electrochemical corrosion if an electrolyte is present, and for this reason a suitable method of corrosion protection is advisable in such cases. The practice is frequently adopted of insulating dissimilar metal parts from one another by a coat of suitable varnish or a layer of paper or fabric impregnated with oil or bitumen applied to the joint before assembly.

#### a. Selection of alloy

**Strength and toughness:** The highest combination of strength and toughness is only obtained in the heat-treated alloys. These should however only be used if high strength is necessary for technical reasons. In many cases it is possible by modifying the dimensions of the design, to make use of non-heated-treated alloys. The conditions of service, whether under impact or fatigue loading, or local stressing of the surface, must be taken into consideration, while for service requiring toughness or insensitivity to effects of notches and suchlike sharp changes of shape, the simpler alloys are to be preferred.

**Casting properties:** Fluidity, contraction, and hot-strength are of greater importance in die casting than in sand casting.

**Working properties:** The heat-treated alloys have the best machining qualities. With heat-treated alloys welding should be avoided owing to loss of strength due to local annealing. Castings in particular should only be welded in exceptional cases. Polishing quality is highest in the heat-treated aluminium alloys, but is also very good in other alloys and the pure metal.

#### b. Anodic oxidation

Anodic oxidation gives to all aluminium alloys in substantially equal measure a high surface protection. The most attractive silvery white transparent oxide coatings are obtainable on Peraluman-3 (Al-3Mg) and -5 (Al-5Mg). Manganese over 0.5 % imparts a cloudiness to the oxide film.

\* Araldit etc.

The decorative effect obtainable with oxide coatings is largely dependent on starting with a dense, fine-grained, non-porous casting and a very careful handling of the surface in manufacture.

*c. Chemical properties*

Castings on which the casting skin has been left untouched are usually more resistant to corrosion than those with machined surfaces. Cold shuts, blow holes and surface defects may form starting points for chemical attack in service. The quality of the casting may have a greater effect than the chemical composition of the alloy of which the casting is made.

In the case of applications in chemical engineering including compressed gases and food stuffs, it is recommended that there should be prior consultation with the aluminium suppliers.

*d. Use of existing foundry patterns*

Patterns made for heavy metals can rarely be used satisfactorily for aluminium castings. Wall thicknesses used for cast iron and bronze can often be reduced for aluminium. Having regard to the lower modulus of elasticity, a sufficiency of strength and stiffness is obtained by some reduction of the wall thickness with at the same time an increase in moment of inertia, obtained by the incorporation of ribs or corrugations and making the shape more box-like. In doing this, care is necessary that the thicknesses of various walls are made as uniform as possible, and that well rounded fillets are always allowed between the various sections.

#### 4. PROTECTION AGAINST CORROSION

It has been mentioned in the introductory remarks that pure aluminium and copper-free aluminium alloys exhibit a high resistance to corrosion. Copper-bearing aluminium alloys are improved in this respect by heat-treatment while magnesium alloys are best dealt with by the application of a special protective treatment. In the presence of liquids, the formation of galvanic couples (local elements) between different alloys may occur. Again, inaccessible places such as joints and crevices should be avoided as some liquid is drawn in and this may become concentrated when the rest gradually evaporates. Intelligent design, construction and maintenance afford an effectual safeguard against corrosion.

TABLE 16

ANTI-CORROSION ADDITION AGENTS (INHIBITORS) FOR DIFFERENT LIQUIDS  
CORROSIVE TO ALUMINIUM

*Corrosive liquid:*

Caustic soda, soda, potash

Aqueous calcium chloride solution,  
Trisodium phosphate,  
Hydrogen peroxide,  
Sodium acetate,  
Hydrochloric acid,

Sulphuric acid,  
phosphoric acid,  
caustic soda.

*Inhibitors:*

Waterglass, glue, agar-agar & other  
colloids, hydrogen peroxide

Waterglass, etc.,

Waterglass,

Waterglass,

Waterglass,

Dibenzyl sulphide,

Hexamethylenetetramine,

Sodium chromate.

Whereas aluminium and its alloys are readily attacked by alkaline liquids, magnesium and its alloys are more resistant to these. The attack of aluminium by these liquids is considerably reduced by the addition of inhibitors. The most effective inhibitors are given in Table 16. The most resistant of the light metals to alkaline liquids are magnesium, pure aluminium, and the Al-Mg alloys.

The most effective protection against the corrosion of aluminium and its alloys is afforded by anodic oxidation, which is rendered still more effective by the after-treatment of sealing and also by subsequent painting. With magnesium also, a protective coating can be given by an anodic oxidation process, but this is less efficacious than the anodic coating on aluminium. Instead, a nitric acid and bichromate dip is mainly used for magnesium alloys.

Owing to its high corrosion resistance, maintenance costs of aluminium structures are appreciably less than for heavy metals. Particularly when compared with steel, the firmly adherent oxide film on aluminium offers a big advantage, being impervious to liquids and gases, and forming a base to which protective paints or varnishes adhere remarkably well. The eating in of rust underneath the paint, which is a source of much anxiety with steel and results in the peeling off of the paint, does not occur with aluminium, and in general the life of paint is greater on aluminium although generally only 2 coats are used instead of 3 for steel. Bright aluminium retains its brightness under the normal action of the weather, if it is cleaned periodically with ordinary metal polish. If this is not done, aluminium will lose its mirror like appearance, but its mechanical properties are not affected. With Raffinal or super purity aluminium, such periodical cleaning is scarcely necessary, and carries the risk that the softer super purity metal is more readily scratched.

It is advisable always to apply a protective surface treatment to magnesium and its alloys owing to their lower corrosion resistance. The most used is a dipping process, in which the article is treated for several minutes in a hot solution containing 10 parts by weight of strong nitric acid in 100 parts of water. The articles acquire from this a golden yellow colour. Magnesium alloys may also be anodically oxidised in a solution of 10% sodium bichromate and 7% sodium monophosphate at 90°C (194°F) and 5 volts. When paint is used it is to be noted that this adheres less well to magnesium than to aluminium alloys. The best practice is to use a priming coat of paint with a zinc chromate pigment. Some synthetic resins form very good protective varnishes.

## CHAPTER V: MELTING FURNACES

### 1. GENERAL

If we look at the melting points and heat contents of various common metals in Table 17, we see that the light metals aluminium and magnesium differ from the heavy metals in having fairly low melting points, but nevertheless require considerable quantities of heat to melt them.

TABLE 17

MELTING POINTS AND TOTAL HEAT ON MELTING OF COMMON METALS

Metal	Mean specific heat-20°C (68°F) to melting point		Melting point		Latent heat of fusion		Total heat to raise unit weight from room temperature to the molten condition	
	°C	°F	°C	°F	kcal/kg (approx)	BThU /lb	kcal/kg (approx)	BThU /lb.
Aluminium	0.25	0.14	658	1216	92	166	250	450
Brass . . .	0.13	0.07	900 (approx)	1675	40	72	140	250
Magnesium	0.27	0.15	650	1202	47	85	220	300
Cast iron .	0.19	0.11	1100—1350	2012—2430	70	126	350	630

To provide the high requirement of heat, special types of furnace are used with sources of heat rather great in volume but rather low in intensity.

The susceptibility of the light metals to gas absorption and their capability of reducing various oxides, such as iron oxide and silica as well as water, influence the selection of the heating agents used and of the furnace lining.

For outputs up to 1 ton of molten aluminium per shift, crucible furnaces are most frequently used, while for greater outputs of similar alloys, reverberatory (or open-hearth) furnaces are more economical. In crucible furnaces, the products of combustion can be prevented from coming into direct contact with the molten metal, but with open-hearth furnaces this is much more difficult to arrange for. For this reason an innocuous furnace atmosphere is to be aimed at, as low as possible in hydrogen and ash con-

tents. The absolutely still atmosphere in electric resistance furnaces, being composed solely of oxygen and nitrogen, combined with the ease and accuracy of control of this type of furnace, make it particularly well suited to aluminium melting.

The tendency of aluminium to reduce foreign substances and to take up impurities from them calls for properly arranged storage conditions for the aluminium pig or ingot, as well as for the cleaning of the scrap if necessary before remelting it. Above all, the metal charged must be completely dry and free from oil and grease. Oily scrap should therefore be degreased. It is advantageous to anneal damp scrap at 300°C (572°F), this often being roasted with air excluded. With foil scrap, particularly, a restricted amount of air is admitted after roasting, to burn off completely all the carbonised paper residues. To reduce the loss by oxidation, thin scrap can with advantage be remelted under a fused salt cover.

## 2. ALUMINIUM MELTING FURNACES

### a. *Crucible furnaces*

Both plumbago crucibles and iron pots are used, the latter being the cheaper and allowing better heat-transmission, while they may be obtained in any desired size. Iron pots give rise to a continuous slow absorption of iron into the metal. The metal suffers least contamination in clay-bound plumbago crucibles. Their smaller thermal conductivity which considerably deteriorates in use through the gradual burning out of the graphite, adversely affects the economy of these crucibles, especially with electric heating. The oxidation of the graphite can readily be reduced by glazing the outer surface of the crucible, and for electric crucible furnaces it is advantageous to use specially glazed crucibles. If such should not be readily procurable, a glaze consisting of 6.1 parts of feldspar, 27.1 soda ash, 106.0 china clay, 104.0 silica sand, 33.8 quick lime, 26.4 dolomite and 167.5 parts of boric acid, as developed by the Research Laboratories of the S.A. pour l'Industrie de l'Aluminium Chippis, can be applied. To restrict absorption of iron from cast iron pots, a dressing of 50% alumina, 45% water and 5% waterglass is used, being sprayed with a spray pistol on to the pot heated to about 100°C (212°F). This dressing is quickly dissolved from the pot by the action of fluxes used in melting and its protective effect is thus reduced, so that it must be applied every day.

For iron pots, a suitable material is a fine grained cast iron with 0.5% graphitic carbon, 3% combined carbon, 0.5% manganese, less than 0.12% sulphur; 0.25 to 0.4% phosphorus and 2 to 2.5% silicon.

Where only small castings are poured direct from hand ladles, fixed

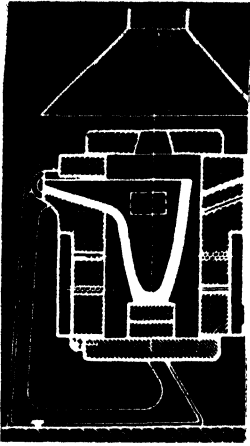


Fig. 102. Tilting coke fired crucible furnace with plumbago crucible.

crucible or pot furnaces can conveniently be used, from which metal is baled out with a hand ladle. For larger cast pieces it is not satisfactory to bale metal out of a fixed furnace by means of a hand ladle and transfer it to a casting ladle, as by doing so considerable quantities of oxide are formed and contaminate the metal. For this purpose tilting crucible furnaces are more suitable (Fig. 102). Electric crucible furnaces should be so constructed that, should a fracture of a crucible take place, the metallic heating elements are not damaged by the molten aluminium which leaks out. To provide for this an outlet can with advantage be left in the bottom of the furnace jacket to allow any such metal to run out into a receiving mould.

In any up to date foundry, means for accurate control of temperature are essential. In electric crucible furnaces, temperature control is applied not only to the metal, but also to the resistance heaters in order to prolong their life. Owing to the relatively low thermal conductivity of plumbago crucibles, there is a temperature gradient of 100 to 200°C (180°-360°F) through their walls. Since the maximum permissible temperature of electric resistance heaters is limited to 1100° or 1200°C (2012-2192°F), the melting rate of electric crucible furnaces is much less than that of coke or gas fired crucible furnaces. In die casting foundries, it is a common practice to melt the metal down in larger furnaces and to transfer it in the molten state to small pot furnaces, placed at each casting station. They are constructed as holding or maintaining furnaces, in which the metal is held

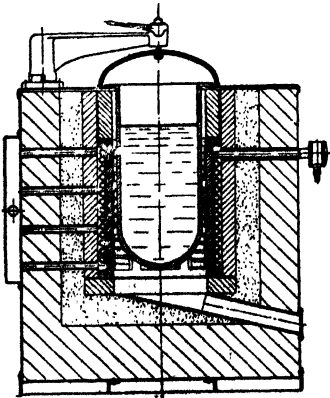


Fig. 103. Tilting electric pot furnace with iron pot.

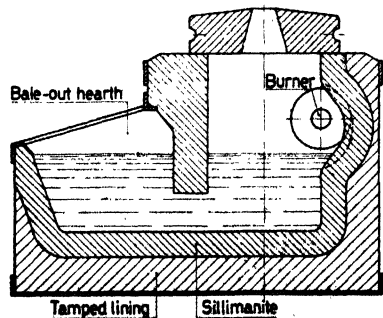


Fig. 104. Forehearth-type melting furnace for gravity die foundries (Schmitz & Co.).

accurately at the correct temperature for casting. To reduce the heat loss arising from the frequent uncovering of such furnaces, they are sometimes built as small open hearth furnaces with a fore hearth, as shown in Fig. 104, this being fitted with a pedal operated fore-hearth cover. In the U.S.A., small Ajax-Tama induction furnaces are now in use for this purpose.

Table 18 gives data on the rating and performance of crucible furnaces.

TABLE 18

RATING AND PERFORMANCE OF CRUCIBLE FURNACES

Aluminium Capacity lbs	Rating kW	Melting rate		Power Consumption kWh/ton
		Iron pots lbs per hr	Plumbago crucibles lbs per hr	
56	15	27	19	700 to 950
220	40	110	75	650 to 800

In holding furnaces the rating is about half the above and the power consumption often runs less than 200 kWh/ton depending on the through-put.

Molten aluminium decomposes water vapour and dissolves the resulting hydrogen with avidity, for which reason plumbago crucibles must be thoroughly dried out before being used. A bare drying out, as is usual in heavy metal foundries, is not sufficient. It can be seen from Fig. 105 that a short heating up of the crucible is not enough to drive out the last traces of moisture. A prolonged heating of the crucible to red heat is necessary to give assurance of an uncontaminated melt. For determining the gas content of molten aluminium, a cylinder 2" diameter and similar height is cast in a sand mould. F1 shows the gas content of metal from the first melt in a crucible dried out and heated in accordance with heavy metal practice. F2 shows the result from a crucible previously heated to redness



Fig. 105. (F. 1) Gas absorption by aluminium in new crucible. (F. 2) Gas-free metal from crucible preheated to redness for 16 hours.



for 16 hours in the furnace. It can be clearly seen that with this method no gas absorption now takes place at all.

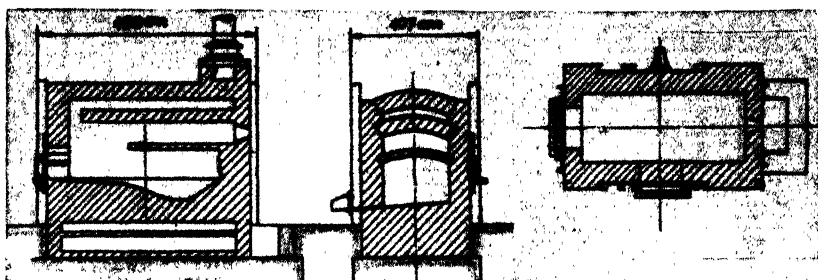
#### b. *Open hearth furnaces*

For larger outputs open hearth or reverberatory type furnaces are utilised. These are operated on either the batch or continuous method. In the batch method, a certain weight of metal is charged into the furnace, melted down, thoroughly stirred and skimmed, then tapped for casting. In the continuous process, additions of metal are made periodically, perhaps every 30 minutes, made up with the required proportions of the alloy constituents, these additions being charged on to the furnace bridge or charging hearth to melt down. Before a further charge is added, any unmelted residue of the previous charge is pushed into the bath. At similar intervals of time, an equivalent portion of the molten metal is tapped from the furnace, leaving a substantial quantity of molten metal still in the furnace. This gives assurance of the most uniform composition possible in the metal drawn off. It is good practice to tap out only 25 to 50% of the contents of the bath each time.

The lining of open hearth furnaces is of ceramic material which must resist attack by aluminium. The material recommended as best for the bath lining is magnesite, or else high alumina firebrick or sillimanite. For all purposes a firebrick with not less than 60% alumina is satisfactory.

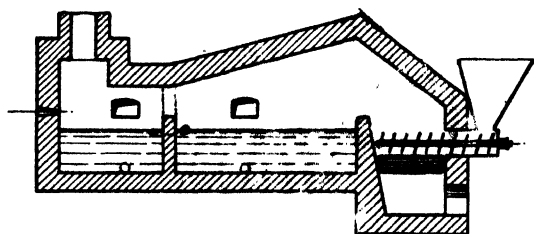
#### (i) *Fuel fired furnaces*

Fuel fired furnaces are generally of the fixed type. At one end are the burners or the fire box and at the opposite end the bridge or charging hearth. The burnt gases are taken off at the end of the charging hearth and heat up the freshly charged metal as they pass out. To increase their thermal efficiency these furnaces are usually provided with recuperators for preheating the combustion air. As already mentioned, it is not considered good practice to bale metal out of stationary furnaces with a ladle, and therefore this type of furnace is usually provided with a taphole which can be closed by a steatite or iron stopper. To reduce contamination of the metal by the burning gases, muffle type furnaces with double roofs, as in Fig. 106 have been developed, which are particularly recommended for oil firing, while for gas firing the burning gases may be taken through the furnace in heat resisting tubes to prevent gas absorption by the metal. Experience has shown that both scrap and ingot metal will absorb moisture in the oxide skin on lengthy storage. If such materials are charged directly in the molten bath, there is an undesirable gas contamination. It



Above

Fig. 106. Oil fired aluminium melting furnace (Pneulec) longitudinal and transverse sections and plan section. Capacity 1500 lbs. Output 3 tons per 8 hrs. Oil consumption 9 gallons per hour.



Left

Fig. 106a. American type open hearth\* melting furnace with double hearth.

is therefore advisable that the metal charged should be preheated on a preheating hearth to  $200-300^{\circ}\text{C}$  ( $392-572^{\circ}\text{F}$ ) before it is charged into the liquid metal. In America, it is now a common practice to use melting furnaces with two hearths, i.e., melting and holding hearths, as shown in Fig. 106a. This has the advantage that the fluxing treatment and the dross arising from it are restricted to the melting hearth only. When the metal is tapped direct from the furnace to a continuous casting machine, all impurities are held back and a sound block free from unsoundness and contamination is obtained. Also, the temperature of the metal in the holding hearth can be held accurately at a predetermined value with the help of the supplementary oil burner located in this space.

## (ii) *Electric resistance furnaces*

In electric resistance furnaces, the metallic resistance heaters are generally accommodated in the furnace roof (Fig. 107). To protect these heating elements from destruction by splashes of molten metal, they are covered by heat-conducting plates. In the middle of the furnace where splashes are most frequent, ceramic plates of silicon carbide are to be preferred,

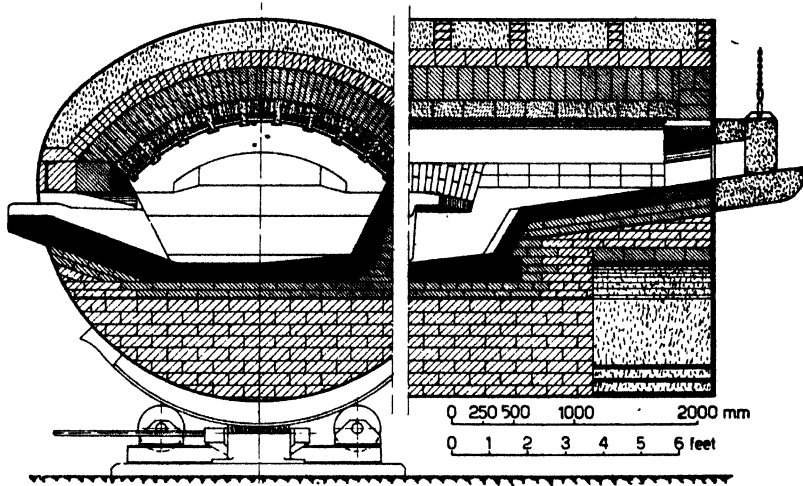


Fig. 107. Tilting electric open hearth furnace (AIAG).

while at the ends it is more satisfactory to use plates of heat-resisting steel having a higher heat conductivity. Owing to the lower furnace temperature at the ends, the heating coils can be run with a higher current density here than in the middle of the furnace. Since failure of the resistance heaters cannot be completely avoided, these should be capable of being readily replaced while the furnace is in operation, without having to cool it down. To avoid an excessive temperature gradient in the plates, the loading of the roof should not exceed about 3 kW per square foot. With this loading the temperature difference is about  $200^{\circ}\text{C}$  ( $360^{\circ}\text{F}$ ), so that with a melting chamber temperature of  $900^{\circ}\text{C}$  ( $1622^{\circ}\text{F}$ ), the resistors must be at  $1100^{\circ}\text{C}$  ( $2012^{\circ}\text{F}$ ). The bricks which carry the heating coils must be of a special quality firebrick which is not attacked by Nichrome nor contains any material which slags with the same, and which has good electrical insulating properties at temperatures up to  $1200^{\circ}\text{C}$  ( $2192^{\circ}\text{F}$ ).

With electric resistance furnaces, it is also to be noted that most volatile fluxes attack the heating elements and rapidly destroy them, so that such fluxes should only be used in the pouring ladle. The careful fluxing and skimming of aluminium before casting is, incidentally, of the utmost importance.

### (iii) *Induction furnaces*

The latest development is the low frequency induction melting furnace for aluminium. In contrast to copper alloys, the light alloys have the unfortunate propensity of forming oxide in the secondary channel or slot of the furnace, which blocks it up after a short time of operation

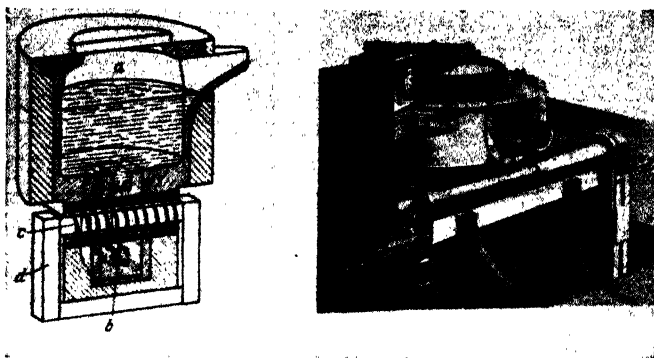


Fig. 108. Induction melting furnace (AIAG—Ajax).

and stops the furnace from working. A periodic cleaning out of the channel(s) is therefore unavoidable, to allow of which the shape and arrangement must be suitable.

In the latest furnaces with improved design of secondary channel, clearing out of the channel(s) is only required at greater intervals of time, and can be done without emptying the furnace off. Thus the operation of the furnace is greatly simplified and interruptions in the melting programme are avoided (USA patent Ajax/Tama).

Fig. 109b shows such an induction furnace of 500 kW with vertical channels or slots. This furnace has another improvement, in having preheating

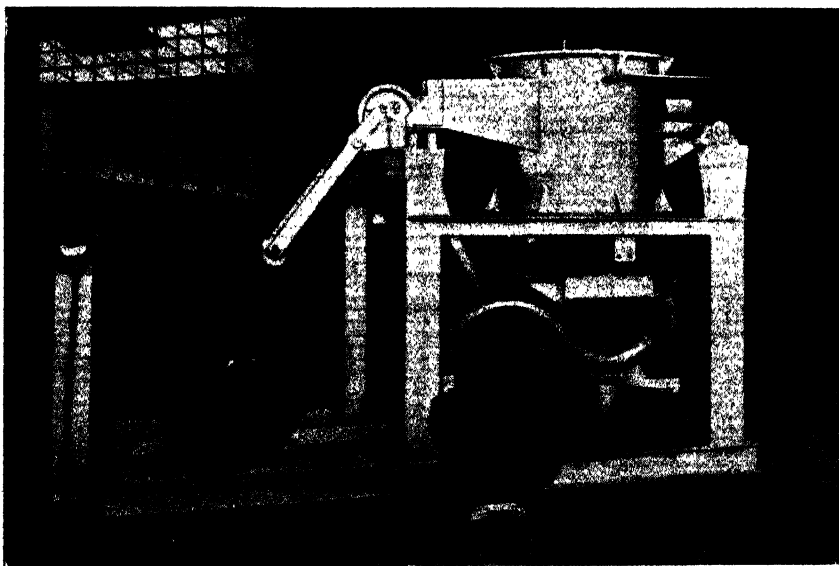


Fig. 109. Induction melting furnace (Gautschi Electro-Fours).

hearth with resistance heaters. This permits a preheating of the charge to about 200 C (392 F), so that any moisture is vapourised before the charge is added to the melt. By this, the gas contamination of the bath is greatly reduced.

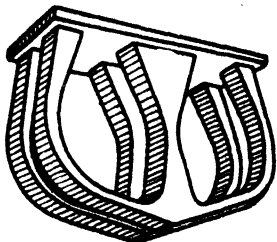


Fig. 109a. Wood form for the secondary channels of a Brown-Boveri induction furnace.

The principle of the induction furnace can be seen in Fig. 108. The primary electrical winding "c" surrounds the iron transformer core "d", the primary phase voltage being usually 300 to 500. The secondary circuit "b" is formed by the molten light alloy. This surrounds the primary coil with one or more parallel rings according to the size of the furnace. A current of low voltage (about 10 volts) and of high ampèreage is induced in the secondary circuit. The molten metal itself constitutes the resistance heater, the heat thus being generated directly in the metal itself. The metal in the induction channel is maintained in circulation by the pinch effect, so that fresh metal is always passing through and thus overheating of the metal in the channel is avoided. The difference in temperature between the metal in the channel and that in the body of the furnace "a" is of the order of only 50°C (90°F). Fig. 109 shows an actual photograph of an induction furnace, the tilting gear for the furnace being on the left, the cooling fan and flexible air pipe for the furnace transformer being in the

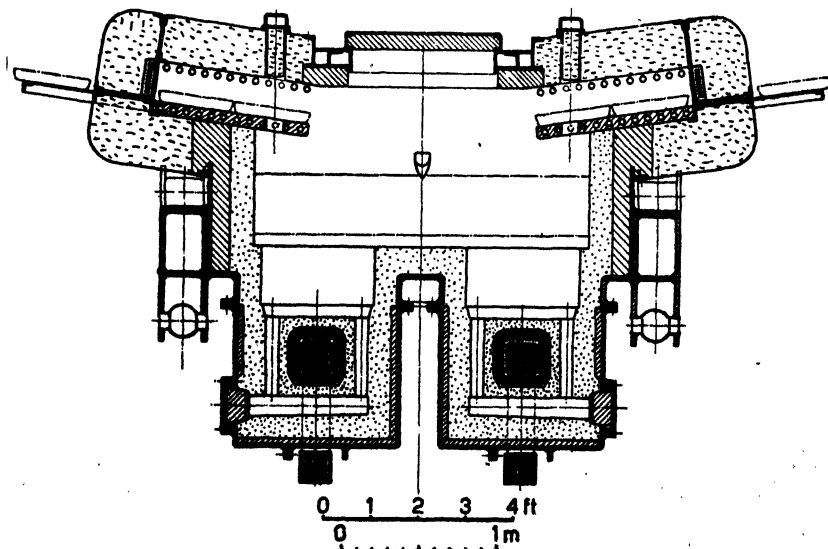


Fig. 109b. Improved type of induction furnace with accessible slots.

(Ajax Tama — A.I.A.G. pat. appl.)



Fig. 110. AJAX induction furnace for melting aluminium scrap.

middle foreground, while the furnace itself can be seen on the right. The main advantage of the induction furnace, beside its outstanding thermal efficiency and high melting rate, lies in its cool atmosphere which keeps down the gas absorption to a minimum. For cleaning out the secondary channels, chain type tools are used, before using which the furnace must be completely emptied out. In starting up the furnace, the channel must be filled with molten metal of which sufficient must be added to close the secondary circuit. In order that metal shall not be slung out by the pinch effect, its level must be at least 4" above the channel.

Since the loading of one channel cannot be much increased, the larger furnaces are built with multiple channels or slots (Fig. 109a).

Fig. 110 illustrates a fixed Ajax induction furnace used for melting aluminium scrap. The rating of this furnace is 250 kW, its capacity 5 tons and the time required to melt down a charge is 8 hours. In the foreground can be seen a casting machine for 2lb. notched bar ingots.

Owing to their restricted superficial electric loading, resistance furnaces of large size are limited to a maximum melting capacity of 10 to 15 tons per 24 hours. The higher superficial loading of induction furnaces permits melting capacities of 15 to 25 tons in 24 hours, which is equal to that of fuel fired furnaces.

## 3. MELTING FURNACES FOR MAGNESIUM

The behaviour of magnesium, in melting differs from that of aluminium in two fundamental ways. In the first place, magnesium reacts exothermically with various ceramic materials, particularly silica and silicates, such as fireclay, and this precludes the use of such materials in contact with the molten metal. Thus magnesium is never melted in ordinary clay-bound plumbago crucibles. In the second place, magnesium does not exert a solvent action on iron so that the metal can be melted in unprotected iron pots.

The much smaller commercial demand for magnesium compared with aluminium means that smaller furnaces are used, and as large cast steel pots are available, it is natural that crucible furnaces are almost exclusively employed. In melting magnesium, fluxes and, usually, sulphur or sulphur dioxide are always used for the prevention of ignition of the metal. The ventilation of the foundry must therefore receive particular attention as also must the protection of the heating elements in electric pot furnaces against the destructive action of the flux vapours. In the last few years the electric magnesium melting furnace has been proved the best in many foundries and this is now to be preferred to oil or gas heated furnaces. As shown in Fig. 111, in contrast to aluminium furnaces, in magnesium furnaces the pot can be lifted out of the furnace and is generally sealed with a sand lute in order to completely prevent the ingress of flux vapours to the resistance heaters. Since in melting magnesium for the production of castings the charges are repeatedly superheated to  $900^{\circ}\text{C}$  ( $1652^{\circ}\text{F}$ ) and cooled rapidly from that temperature to the casting temperature of  $700$  to  $750^{\circ}\text{C}$  ( $1292^{\circ}$ - $1382^{\circ}\text{F}$ ), the pot must be capable of being readily lifted from the furnace. To lessen the scaling of the external surface of the pot, it is often sand-blasted then sprayed with aluminium from a metal-spraying pistol, which forms a non-oxidising Fe-Al coating on heating. Or the pot is externally nickel plated (Toraxed) or coated with a non-oxidising nickel-chrome coating applied by means of electric welding rods. The use of heat-resisting metal pots is not permissible owing to the dissolution of nickel and chromium by the molten magnesium.

The smaller sized pots of under 400 lbs capacity are made of welded mild steel plate. Since the attack on the crucible is strongest at the slag line,

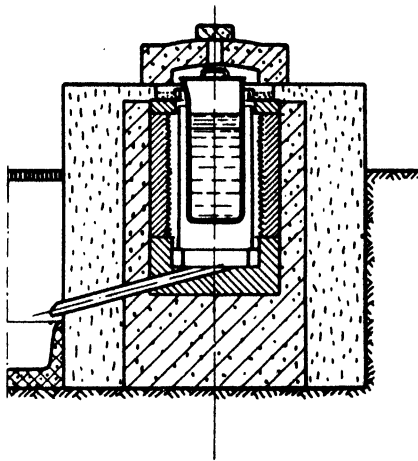


Fig. 111. Electric pot furnace for magnesium melting (AIAG).

the wall of the pot is usually made thicker in this zone than below. Pots up to 200 lbs capacity have walls  $\frac{1}{2}$  to  $\frac{5}{8}$  inch thick in the upper part and  $\frac{5}{16}$  to  $\frac{1}{2}$  inch below, while larger crucibles are proportionally thicker. For capacities over 500 lbs, cast steel pots with wall thicknesses of  $1\frac{1}{4}$  to  $1\frac{1}{2}$  inches are the usual practice.

Since a leakage of the crucible would be extremely dangerous owing to the combustible nature of magnesium, the pots must be subjected to an examination after 24 to 40 working hours. First the flux and slag incrustations are leached off by filling the pot with water, and leaving to stand for some 24 hours. Then follows a careful examination of the outer and more particularly the inner surface of the pot. Suspicious looking places are tapped with a hammer. Weak spots often show themselves on the outer surface during the leaching process by the water weeping through the porous places. These are cut out and made good by welding-in pieces of plate. If the external protective coating is defective, it is renewed during the examination. By careful attention, mild steel pots may last for 80 to 100 heats before repair. Periodic renovation ought to make them good for 150 to 200 heats. Thick walled cast steel pots should last up to 350 heats.

At the present day in America, open hearth furnaces of 1 to 10 tons capacity are in use for magnesium. The melting hearth is constructed of silicon carbide "Tercod" refractories which are protected from damage by the molten magnesium by means of an inner carbon lining. The melting hearth can alternatively be built with confidence from magnesite brick or moulded with magnesite aggregate.

#### 4. RECLAMATION OF METALLIC ALUMINIUM AND MAGNESIUM FROM FOUNDRY RESIDUES SUCH AS SKIMMINGS, METALLICS, SLAGS, ETC.

In spite of refinements in practice with the object of minimising metal losses in melting, casting and refining, some metal values are unavoidably lost in furnace skimmings, splashings and ladle skimmings, etc. Thus the question of reclamation is of very definite interest.

There are no hard and fast rules as to the minimum quantities of residues (metallics, skimmings, dross, sweepings, etc.) that should be accumulated before treatment is applied; generally speaking the working up of 7 to 10 tons of residues a week is considered as worth while. The equipment required is simple, requiring but little power and attendance. The procedure consists in grinding the residues, whereby the metallic particles are but little altered, while the non-metallic portions are reduced to powder, whereupon the two classes of product are separated by sieving or air separation. The exact layout of the plant depends on the quantities and types of residues to be dealt with.



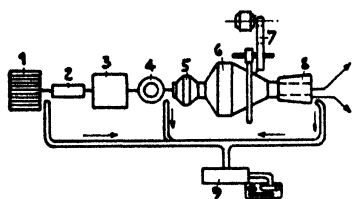


Fig. 112. Plant for reclamation of aluminium or magnesium from skimmings (Karl Schmidt)

- 1 Hand breaking grid.
- 2 Elevator.
- 3 Vibrating sieve.
- 4 Measuring skip.
- 5 Feed box.
- 6 Conical ball mill.
- 7 Drive.
- 8 Conical double trommel screen.
- 9 Pneumatic dust collector.

For grinding, a continuously operating ball mill is used. Large pieces of scrap, such as skulls, must be broken up small beforehand.

In the small plant laid out as in Fig. 112, for handling 750 lbs per hour, the sieve is a conical trommel screen placed right at the discharge of the ball mill, and has two concentric wire screens of  $\frac{1}{4}$  inch and  $\frac{1}{16}$  inch mesh. The metallics retained on the screens are collected and passed to the remelting process. The fines which pass through the screens consist mainly of oxide and are of no further use.

## 5. WORKING UP OF SCRAP

With the increasing consumption of aluminium, there arise considerable quantities of scrap to be handled. This may arise as process scrap in the fabrication of aluminium and its alloys, and which is either consumed in the same fabricating processes, or is sold to scrap dealers or foundries, or else is accumulated as discarded aluminium articles and parts. The distinction between virgin aluminium and secondary aluminium is not hard and fast. In some places only metal from the aluminium reduction furnaces cast directly into blocks is recognised as virgin metal, but in general it is held that process scrap in rolling mills and presswork plants remelted with a reasonable addition of virgin pig may still be designated as virgin metal.

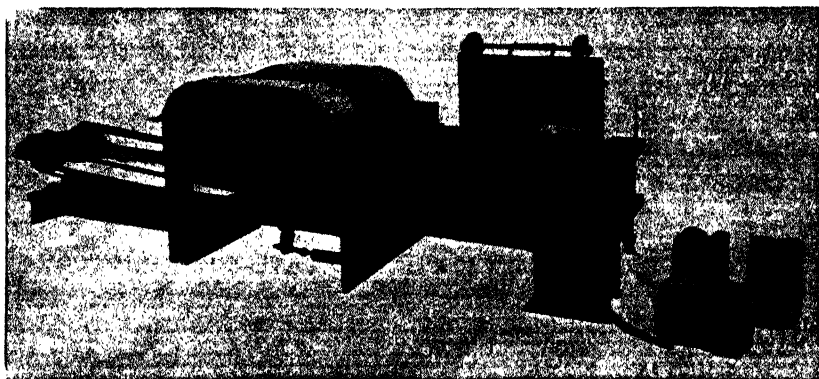


Fig. 113. Scrap baling press (Heenan & Froude, Ltd., Worcester, Eng.).

Scrap is classified according to its origin as under:

1. New and old pure aluminium sheet scrap.
2. New and old pure aluminium cable scrap.
3. Pure aluminium utensils.
4. Aluminium alloy casting scrap.
5. Sheet, extruded and forged parts.
6. Aluminium turnings and other machining swarf segregated by alloys.
7. Mixed alloy scraps.
8. Melting furnace skimmings.

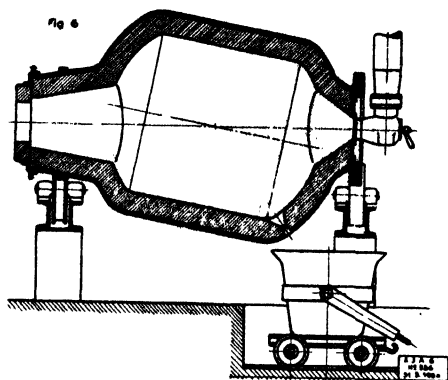


Fig. 114. Barrel furnace for melting up fine scrap and metallics.

merchants and secondary smelters. Tables 5 and 5a give a representative selection of contemporary Swiss and British secondary alloys.

To reduce loss of metal by drossing, fine scrap, such as thin sheet, foil, turnings and other machining swarf is with advantage baled in a scrap baling press (Fig. 113). For melting up loose swarf and small scrap, a barrel furnace as in Fig. 114 is suitable, in which a bath of salt flux consisting of 85% NaCl, 10% cryolite, 5% KCl is first melted down. The furnace is continuously rotated and the scrap thereby is at once submerged in the molten flux. The loss of metal as dross is thus reduced to a minimum. For some years, electrically heated salt bath melting furnaces have been in use, in which, as shown in Fig. 114a, the electric current is led into the molten salt by carbon electrodes, the required heat being generated

Of these, only clean pure aluminium scrap and segregated alloy scraps have a high value. It is not advisable for any one to concern themselves with the working up of scrap without the necessary experience, but to leave this business to the scrap metal

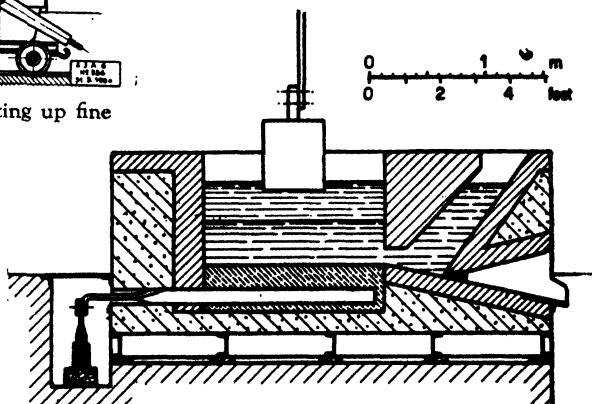


Fig. 114a. Electric salt bath for scrap melting.

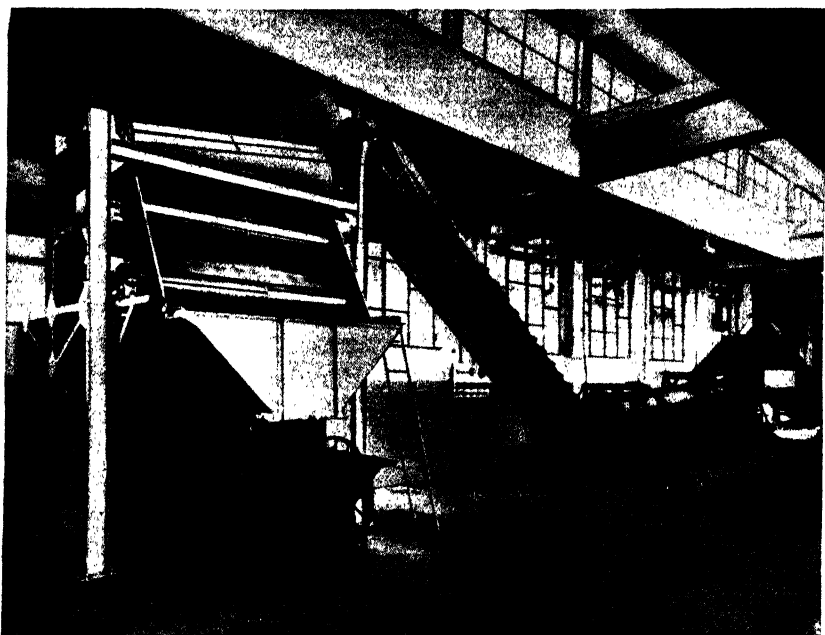


Fig. 115. Pre-treatment plant for scrap (Pontzen).

by the resistance of the molten salt itself. For remelting of thin machining chips and swarf, which can be charged direct without briquetting, these furnaces give the lowest metal loss in melting and the best metal quality. The composition of the salt for the bath is the same as that given above for barrel furnaces, or alternatively, 30% cryolite, 15% potassium chloride, 55% sodium chloride.

Before the scrap is melted up, it is common practice to subject it to a preparatory treatment. Fig. 115 illustrates a suitable plant for this, in which the scrap is first heated to 300°C (572°F) in a rotary kiln to dry it and burn off any organic matter. This delivers by a conveyor to a trommel screen and thence the material passes across a magnetic separator which completely separates all pieces of iron from the light metal. Preceding this equipment, a shearing machine is often installed, in which the scrap is cut up to a maximum size of 2 to 4 inches.

## 6. MELTING COSTS

The operating costs of the various methods of melting depend very largely on the nature of the material charged, as loss by drossing, as shown in Table 19, is an important factor.

TABLE 19

## LOSS ON MELTING VARIOUS MATERIALS

Pig metal . . . . .	0.8 to 2%
Thick scrap . . . . .	1 to 3%
Baled sheet scrap. . . . .	1.5 to 4%
Briquetted foil scrap . . . . .	2 to 10%

The gross loss is lowest in electric furnaces and highest in open flame furnaces. Flux baths are only used in the case of finely divided material. Table 20 gives a comparison of operating costs in melting metal for rolling blocks in different types of furnace, the skimmings being treated periodically in the furnace with 10% of their weight of special flux before raking off in order to reduce the metal loss. In this way the metal content of the skimmings removed is reduced by more than half. In large scale operations, a further 25% of low purity aluminium is recovered from the furnace skimmings by special processing of the skimmings.

TABLE 20

## OPERATING COSTS FOR MELTING ONE TON OF METAL IN DIFFERENT MELTING FURNACES (APPROX.)

## COKE FIRED OPEN-HEARTH FURNACE

Loss of metal as dross 42 pounds @ 8.8d, say. . . . .	30s-10d
Coke consumed 391 pounds @ 65s per ton, say. . . . .	11s- 5d
Wages 12 man-hours @ 2s-2d, say . . . . .	26s- 0d
Repairs (material and wages) . . . . .	7s- 0d
	<hr/> 75s- 3d

## CARBON RESISTOR (CHANNEL) FURNACE

Loss as dross 24 pounds. . . . .	17s- 7d
Power 550kWh @ 0.7d, say . . . . .	32s- 1d
Gas carbon 9 pounds @ 1d. . . . .	9d
Wages 2 men, 550 pounds per hr—8 man-hours per ton. . . . .	17s- 4d
Repairs . . . . .	3s- 6d
	<hr/> 71s- 3d

## NICHROME RESISTANCE FURNACE

Loss as dross 24 pounds. . . . .	17s- 7d
Power 450kWh . . . . .	26s- 3d
Wages 2 men, 550 pounds per hr—8 man-hours per ton. . . . .	17s- 4d
Repairs (heating elements, shielding plates, etc.) . . . . .	4s- 0d
	<hr/> 65s- 2d

## INDUCTION FURNACE

Loss as dross 18 pounds. . . . .	13s- 3d
Power 430 kWh . . . . .	25s- 1d
Wages 3 men for 600 pounds per hr—11 man-hours per ton. . . . .	23s- 1d
Repairs . . . . .	1s- 6d
	<hr/> 62s-11d



Fig. 116. Drying stove for fluxes.

## 7. FLUXES

Fluxes are in general use in melting aluminium. They are used for different purposes, namely,

1. to lessen oxidation and gas absorption,
2. to exert a purifying action on the aluminium,
3. to remove any dissolved gases.

All the usual fluxes (except gaseous or gas-generating fluxes) are hygroscopic. Any moisture which is introduced into the molten metal gives rise to an absorption of hydrogen gas into the metal due to the decomposition of the water. In preparing the fluxes, therefore, careful drying of the same must receive attention and the flux must be protected in subse-

quent storage from renewed moisture absorption by being kept in tightly closed metal containers. It is a good plan to take out at once sufficient flux

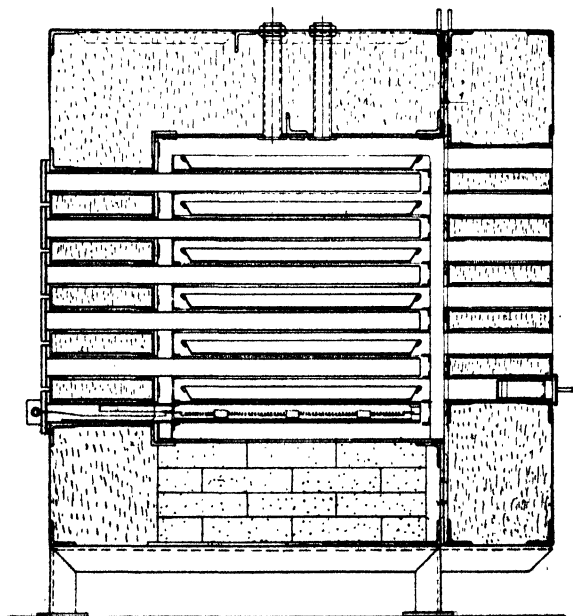


Fig. 117. Drying stove for fluxes in longitudinal section:

to last for one day, as the periodic opening of the container lets in the moisture. Figs. 116 and 117 show a stove for drying the ingredients of the flux before mixing, as well as the mixed flux before using it. Such stoves can be installed with benefit in larger foundries and casting shops.

TABLE 21

## COMPOSITIONS OF FLUXES IN GENERAL USE

Group 1:	1. 85% NaCl 15% Chiolith	2. 75% NaCl 10% KCl 15% $\text{Na}_3\text{AlF}_6$
Group 2:	3. 60% NaCl 25% KCl 15% $\text{Na}_3\text{AlF}_6$	4. 35% NaCl 15% $\text{Na}_2\text{CO}_3$ 50% $\text{Na}_3\text{AlF}_6$
	5. 40% NaCl 40% KCl 20% $\text{Na}_3\text{AlF}_6$	6. 30% NaCl 40% KCl 15% $\text{Na}_2\text{CO}_3$ 15% KF
Group 3:	7. 75% NaCl 20% $\text{ZnCl}_2$ 5% KCl	8. 20% $\text{Na}_2\text{SiF}_6$ 10% KF 40% NaCl 30% KCl
For Mg-rich alloys :	9. 65% $\text{MgCl}_2$ 25% KCl 5% NaF 5% $\text{CaF}_2$	

The effect of the fluxes on the fluidity and strength of various alloys can be seen in Fig. 118. Table 21 gives the compositions of some common fluxes of the three groups referred to above. For high-magnesium aluminium-

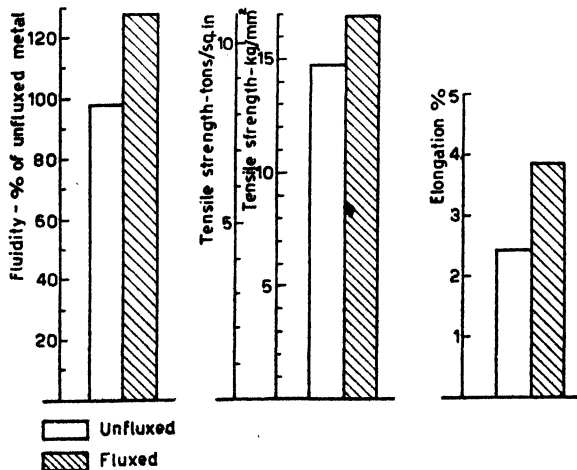
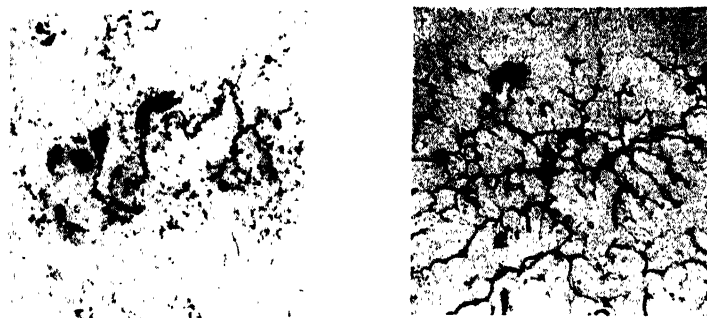


Fig. 118. Effect of fluxes on fluidity and mechanical properties of aluminium alloys.

base alloys as well as for magnesium alloys, a special flux is used whose principle ingredient is magnesium chloride, since the other fluxes, especially those containing fluorides, tend to reduce the content of magnesium



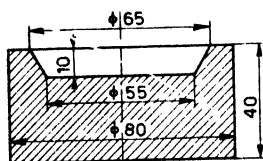
Slowly cooled

Rapidly cooled

Fig. 119. Effect of rate of solidification on appearance of blow holes.

in the alloy. This flux is so very hygroscopic that it is best to melt it before adding it to the metal.

The application of fluxes is usually carried out in the pouring pot at a metal temperature of 730° to 800°C (1346°-1472°F) as a maximum. The flux is generally wrapped in weighed quantities in aluminium foil and is



Carbon mould for  
cast test specimen

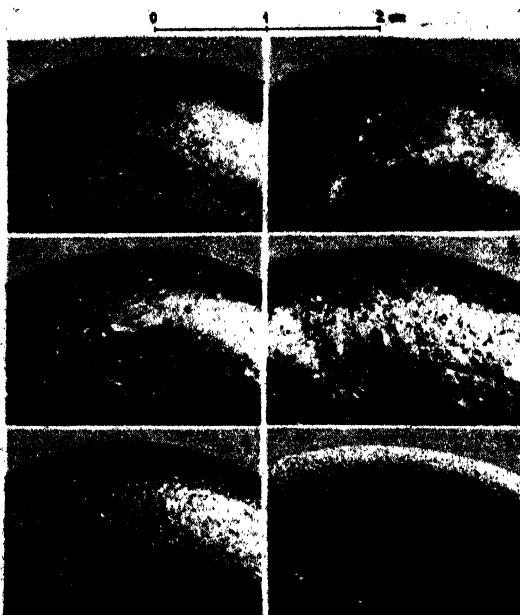
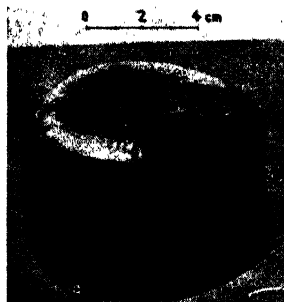


Fig. 120. Casting test for estimation of gas content.

plunged quickly under the molten metal by means of a fluxing bell. In remelting light scrap, a molten flux bath should be first prepared in the furnace into which the scrap is immediately submerged. Magnesium alloys must always be melted under a molten flux cover owing to the danger of ignition of the metal, and this as a final process is stirred thoroughly into the molten metal for the purpose of removing impurities.

Gases dissolved in the metal separate out during solidification, usually in the form of gas bubbles. According to the alloy and to the rapidity of solidification these appear either in the form of spheroidal bubbles or in the shape of interdendritic segregates at the grain boundaries (Fig. 119). Before casting therefore, it is important to ascertain that the metal is gas-free. A simple method for this is the use of the cast test specimen proposed by the Metallgesellschaft (Fig. 120). For this, a quantity of about 100 grammes of the molten metal is cast in a carbon or firebrick mould preheated to  $100^{\circ}$  to  $200^{\circ}\text{C}$  ( $212^{\circ}$ - $392^{\circ}\text{F}$ ). During the slow cooling, the liberated gas content is given the opportunity of appearing at the surface in the form of fine pimples. It is thus important that the solidification proceeds slowly, and therefore a metal mould may not be used. The number and size of the gas bubbles appearing at the surface afford a measure of the gas content of the metal. If only isolated bubbles of the first type occur, the gas content may be accepted.

A more accurate test, known as the STRAUBE-PFEIFFER (Fig. 121), is carried out by allowing a sample of the metal in a cast iron crucible heated



Fig. 121.  
Straube-Pfeiffer apparatus for  
estimation of gas content.

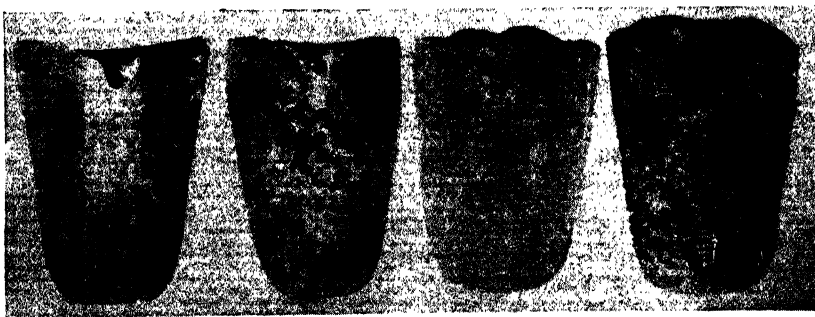


Fig. 122. Straube-Pfeiffer test specimens with different gas contents.



to redness to solidify in a vacuum bell. During solidification, the emission of gas as bubbles from the surface of the metal can be observed through the sight glass. After solidification, the regulus or ingot is sawn in two in order that the gas which has separated in the last stage of solidification, and which has not been able to escape at the surface, may be observed. Fig. 122 illustrates the appearance of such a specimen of metal from this test with a high gas content.

Dry nitrogen or chlorine gas bubbled through the metal is often used for degassing. The first named merely sweeps out the gas mechanically but chlorine acts chemically through the formation of aluminium chloride. According to RIEDELBAUCH, an oxygen carrier for the oxidation of the hydrogen, and chlorine for sweeping it out are led into the metal. Other proposals cover chlorine-generating materials, such as hexachlorethane, as the purifying agent, or  $\text{NaBF}_4$  combined with salts.

TABLE 22  
FLUXES FOR MAGNESIUM MELTING

	1	2	3	4	5	6	7	8	9	10	11	12	13
$\text{MgCl}_2$ . . . . %	53	68	14	34	50	70	31	60	50	37	—	—	—
$\text{NaCl}$ . . . . %	12.5	—	31	—	—	—	—	—	—	5	—	—	—
$\text{KCl}$ . . . . %	33	24	11	55	20	—	37	—	—	10	57	23	—
$\text{CaCl}_2$ . . . . %	—	—	44	—	—	—	—	—	—	14	28	—	—
$\text{NaF}$ . . . . %	—	5	—	—	—	—	6	—	—	—	—	—	—
$\text{CaF}_2$ . . . . %	—	3	—	2	15	20	21	—	—	21	2.5	2.5	13
$\text{MgF}_2$ . . . . %	—	—	—	—	—	—	—	40	20	—	—	—	—
$\text{MgO}$ . . . . %	1.5	—	—	—	15	10	5	—	10	13	—	—	11
$\text{MgCO}_3$ . . . . %	—	—	—	—	—	—	—	—	20	—	—	—	—
$\text{BaCl}_2$ . . . . %	—	—	—	9	—	—	—	—	—	—	12.5	2.5	—
$\text{MnCl}_2$ . . . . %	—	—	—	—	—	—	—	—	—	—	—	72	76

No. 4 corresponds to the American flux No. 230

" 5 " " " " " " 310

" 11 " " " " " " " 220

" 12 " " " " " " " 250

" 13 " " " " " " " 320

For remelting and purifying magnesium, the magnesium chloride base fluxes as given in Table 22 are used. These fluxes are very limpid, and envelope the metal during melting, sinking to the bottom with the impurities after a short time, whence they are ladled out. They should be used also to protect the surface of the molten metal against oxidation. The fluxes 1 and 2 in the table are typical examples. In fluxes 3, 10 and 11, a portion of the expensive  $\text{MgCl}_2$  is replaced with economy by  $\text{CaCl}_2$  (British patent 561,748).

The purification is completed when further additions of flux do not sink below the metal. A flux is then added which is rather viscous and

simply serves as a cover. This flux should form a crust on the melt and it prevents the ingress of air during the superheating of the metal to 900°C (1652°F), as well as during the period of casting. For thickeners,  $\text{CaF}_2$ ,  $\text{MgO}$  and more rarely  $\text{MgF}_2$  are used. Examples of these fluxes are numbers 5 to 9 in the Table. In the viscous as well as in the limpid fluxes, the expensive  $\text{MgCl}_2$  is partly replaced by  $\text{CaCl}_2$  according to the above mentioned British patent.

#### 8. MODIFICATION OF THE ALUMINIUM-SILICON ALLOY

Unlike other aluminium casting alloys, in sand castings of the aluminium-silicon alloys, Alpax, Silafont or Wilmil (C: Al-12 Si), the finely dispersed or modified structure of the eutectic is obtained by the addition of a modifying agent, the active constituent of which is sodium. In die castings, the rapidity of solidification is so high that generally modification is brought about by the chilling and a finely dispersed eutectic results from the process.

The molten metal at a temperature of 850°C (1652°F) is covered with a fluxing mixture of potassium, sodium and calcium salts. One of the different compositions recommended for this contains:

Sodium chloride	20%
Potassium chloride	20%
Calcium fluoride	25%
Sodium carbonate	35%

After several minutes, during which the melt will have cooled somewhat, 0.3% of metallic sodium wrapped in aluminium foil is plunged through the flux cover and into the molten metal by means of a small inverted crucible, and well stirred about. After standing for several minutes, during which it cools further to the casting temperature of 720° to 750°C (1328-1382°F), the metal is ready for casting. For testing the modification, a portion of the flux cover on the surface is skimmed aside. The initial bright silvery surface of the metal should become dimmed with a blue film after a few minutes. Should the film come immediately, the time of standing has not been sufficient. On the other hand should the film not appear for a rather long time, or scarcely at all, the time of standing has been too long, or the sodium addition insufficient. For perfect castings of this alloy, the proper conditions for modification and casting must be accurately maintained.

## PART II. FABRICATING PROCESSES

### CHAPTER VI: CASTING

#### 1. GENERAL. ALUMINIUM CASTING

The starting point of all metallurgical fabrication is the casting of the metal into the required shape. The foundry uses small 2-pound notched bar ingots, or larger ingots or pigs of 10 to 56 pounds in weight, according to the quantity of metal required: the rolling mill uses rectangular rolling blocks, and the extrusion factory round billets of various sizes. Fig. 123 shows a collection of such ingots and blocks. When alloys are fabricated, the necessary alloying additions to the pure aluminium are made in the casting process. Ingots are generally produced at the reduction works, but it is usually more convenient to cast the rolling blocks, extrusion and forging billets at the fabricating works. In doing this, the scrap arising in the fabrication is blended in with virgin metal and is thus used up. At the reduction works, the metal tapped from the electrolytic reduction furnaces is transferred to large mixing ladles or refinery furnaces, and is

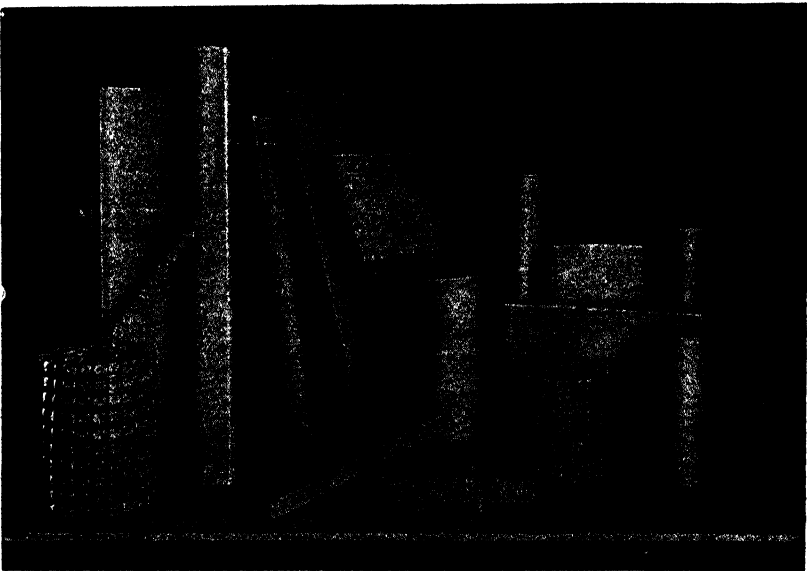


Fig. 123. A collection of light metal ingots, blocks and billets.

cast from these direct into the required shape, the object of the latter being to obtain a close uniformity of composition. When contaminated scrap is to be worked up, it is not an unusual practice to melt this twice in order to secure a superior composition. In such a case, some impurities settle to the bottom in the first melting operation. This process is used considerably in the refining of aeroplane scrap. The first casting is into ingots and these are remelted, usually with the addition of some virgin metal, and cast into the required size of blocks. In the case of a works where the only scrap arises from virgin metal and this forms the addition when virgin ingot is remelted, the product still qualifies for the designation virgin metal. When scrap is brought in from another source, however, the resulting blocks are then designated secondary metal. For successful fabrication in rolling, extrusion and forging, the quality of the blocks or billets which form the starting point of these processes is of paramount importance. Defects arising in casting frequently only become manifested at the finished stage of the semifabricated material; thus the casting process must receive very special attention. As the tendency of molten aluminium at increased temperatures is not only to absorb an increased quantity of gas but also to solidify with an increased coarseness of crystal size, it follows that overheating of the metal above  $800^{\circ}\text{C}$  ( $1472^{\circ}\text{F}$ ) is to be avoided.

Aluminium may be cast both in sand moulds or in permanent metal moulds (or dies). In metal mould casting, we distinguish between gravity die castings (or metal mould castings), and pressure die castings, which include those made in air-pressure machines and those in hydraulic or cold chamber machines (press castings and pre-castings).

## 2. INGOT CASTING

The metal is cast originally in different forms to suit the requirements of further manufacturing. For foundries, pure aluminium is generally cast in notched bars of about 2 pounds weight which are bundled with wire into one hundredweight bundles. The casting alloys on the other hand, are supplied in 10 to 56 pound ingots or pigs, partially divided by two notches, while for sheet rolling, flat blocks or slabs up to two tons weight are cast, and the wire industry take wire-bars 3 to 5 inches square and up to 5 feet in length. For extrusion, round billets of diameter suitable for the press container up to 20 inches and length up to 3 feet are used. For tubes, the extrusion billets are cored or bored.

Ingots of casting alloys are always cast in cast iron moulds or chills. In large casting shops, casting machines are employed, as illustrated in Fig. 124. In smaller works a frame of ingot moulds is used, into which the metal may be poured from a ladle on wheels. In general, rapid solidi-



Fig. 124. Ingot casting machine (Bühler, Uzwil).

fication results in a fine-grained crystal structure in the ingot. When the moulds become excessively hot in use, the rate of solidification is retarded and the ingots will then be coarse grained. While a coarse structure is a thing to be avoided in castings, rolling blocks and billets, such a structure is of no importance in ingots for subsequent remelting. The surface of the ingots also is affected by the rate of solidification. In hot chills, the slowly cooled ingots often have a rough surface showing the crystal structure, but rapidly

solidified ingots from the same melt will show a smooth surface. This appearance is also without effect on the metal quality, provided that the metal has not been heated above  $800^{\circ}\text{C}$  ( $1472^{\circ}\text{F}$ ), nor been gassed with water vapour emanating from the furnace atmosphere, the crucible or the melting hearth. Even gassy ingots can, however, be degassed to a satisfactory degree by correct remelting and fluxing conditions.



Fig. 125. Ingot casting from ladle carriage.

## 3. BLOCK AND BILLET CASTING

For manufacture by rolling, extrusion and forging, blocks and billets of various dimensions and weights are required. In order to decrease

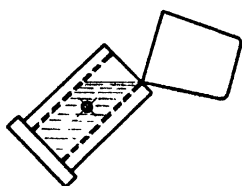
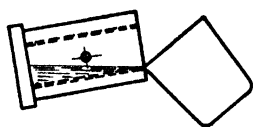


Fig. 126. Casting of light metal rolling blocks in tiltable chill.

the cost of production, the trend is towards bigger and bigger blocks up to 2 tons and more. The block casting process has undergone a fundamental change in the last few years. Originally blocks and billets were cast in horizontal flat moulds. As a sink formed in the upper surface of the blocks cast in this manner, these were turned on the side for casting, and there then came the danger of internal unsoundness from the pipe formed under this condition. The next step was casting upright with the greatest axis vertical. Since, however, aluminium may not be teemed straight into the mould in an open stream as may copper, the mould must be tilted at  $70^\circ$  at the commencement of pouring, as shown in Fig. 126, so that the metal can be poured quietly down the valley-shaped narrow side of the mould. As pouring proceeds the mould is gradually turned back to the upright position at such a rate that the surface of the molten metal in the mould is always nearly level with the upper corner, as shown in the illustration. Fig. 127 shows that this method of filling the mould gives rise to a continuous motion in the metal which affects the uniformity of the solidification. For the test shown, the mould was first half filled with a copper-containing aluminium alloy, and pure aluminium was poured in for the second half. The dark colour of the copper on etching a macrosection of the block renders visible the movement of the portion that contains the copper. Since the solidification shrinkage of aluminium amounts to 7.1%, a considerable diminution of volume takes place on solidification which must be made up by progressive feeding or topping up with hot metal. Fig. 128 shows how extensive is the distribution of the feed metal in a pure aluminium block, the course of copper-containing feed metal in a test being rendered visible by etching in a similar manner to Fig. 127. It is clear from this that a careful feeding with uncontaminated metal is of the utmost importance. In practice of course, metal of exactly the same composition as the block must be used for feeding. Since the residual metal in the casting ladle is not hot enough for feeding, special



Fig. 127. Flow of metal in tilting the mould.



Fig. 128. Pipe formation (left) and effect of feeding (right) in block casting.

to 572°F) for pure aluminium as against 100° to 200°C (212° to 392°F) for aluminium alloys. Since the cooling of the moulds is time-consuming, watercooled moulds as in Fig. 129 are preferred. During block casting, the cooling water is generally not put on until the mould is full, when it is turned on slowly. To accelerate solidification during the casting of the block, this is cast as slowly as possible, and takes 3 to 4 minutes for a 200 lb. block, the subsequent feeding lasting for 10 to 20 minutes.

Owing to the relatively slow solidification proceeding from the outside towards the interior, inverse segregation takes place, in which the impurities and alloying additions tend to concentrate at the surface of the block. This phenomenon has its origin in that the alloy constituents form alloys of low melting point with aluminium, which on solidification collect at the boundaries of the crystals of the primary metal. Through the contraction of the cooling metal, these still-liquid boundary-segregates are expressed towards the outside and cause an enrichment of the skin. With pure aluminium with 0.4% each of Fe and Si, there is found on the outermost

metal for feeding is generally kept hot in small feed-metal pot furnaces.

The time of solidification of a block depends on the rate of dissipation of its latent heat. The high latent heat of fusion of aluminium of 92.4 kcal/kg (166.3 BThU's per lb.) gives in a 100 kg or 220 pound block a total liberation of heat of 9240 kcal or 36600 BThU's. This heat must in the first place be taken up by the chills, which will then be found to undergo a rise in temperature of about 100°C (180°F). In view of the specific heat of iron at 300°C (572°F) being about 0.14, a chill mould of about eight times the weight of the aluminium is advisable. Before the next block is cast in it, the mould must be cooled down to the correct mould temperature for the commencement of pouring, which depends on the composition of the metal being cast, and is about 250°C to 300°C (482°



Fig. 129. Water-cooled billet mould (Junker).

.004 inch thick skin 2% Fe and 0.6% Si, and at .02 inch below the surface there is still 0.55% Fe and 0.4% Si. At .04 inch below the surface the composition is the average of the block. The higher the alloy content, the more pronounced is the inverse segregation. With the Al-Cu-Mg alloy with 4% Cu, the copper found in the surface zone to a depth of .04 inch is as high as 15 to 20%, and at a depth of  $\frac{3}{8}$  inch it is still 4.5%, while in the central portions, the copper content only amounts to 3.8% (Fig. 130). Apart from this segregation, the slow solidification gives rise to a coarse crystal size, especially with heavy blocks, which tends to give rise to difficulties in the working processes of rolling and forging. The crystal size is also strongly influenced by the casting temperature, and for this reason the pouring should always be done at



Fig. 130. Segregation of copper on casting in a cast iron mould  $\times 25$ .



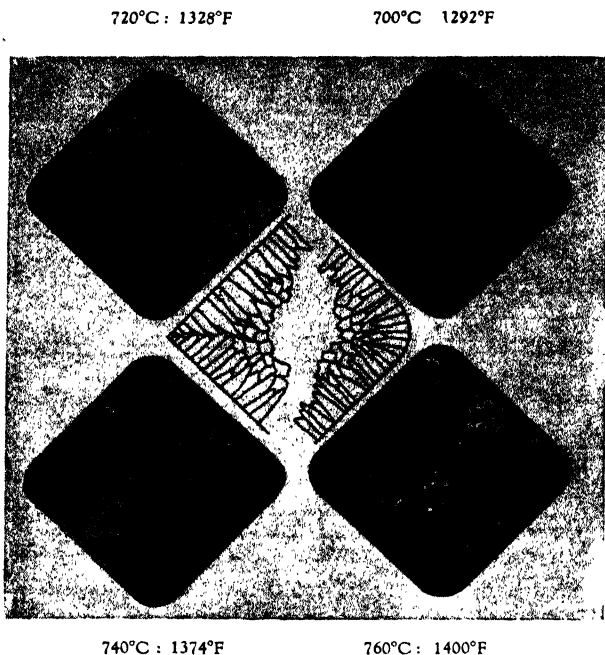


Fig. 131. Effect of pouring temperature from 700°—760°C (1292°—1400°F) on the crystal size.

the lowest possible temperature. Fig. 131 illustrates the block structure with metal temperatures of 700° to 760°C (1292° to 1400°F) by 20°C (36°F) increments, the increasing crystal size being clearly visible. In the middle of the illustration the effect of rounded corners on the formation of the columnar crystals is shown schematically. Furthermore, overheating of the aluminium in the melting furnaces also promotes a coarse crystallisation notwithstanding subsequent cooling to the correct pouring temperature, and thus all over-heating in the melting furnace is to be avoided.

On the grounds of economy the practice is sometimes adopted of casting direct from the furnace into the mould, as shown in Fig. 132. This practice has the advantage that the temperature of the metal in the furnace may

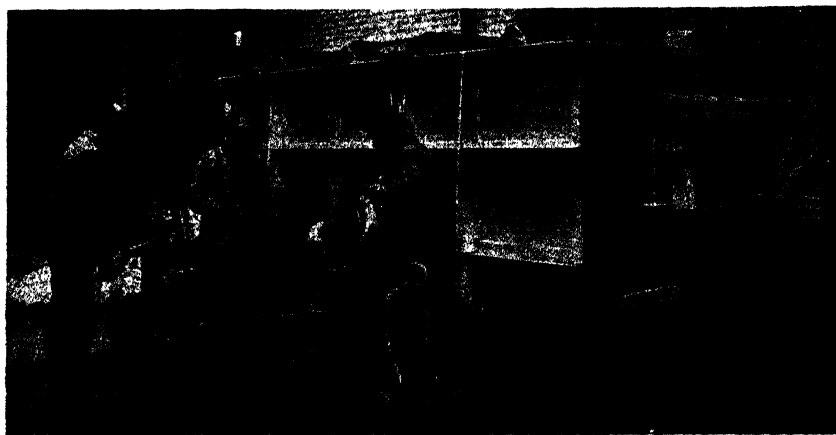


Fig. 132. Direct casting of rolling blocks from an electric resistance furnace (Brown, Boveri and Co./Gautschi, Menziken).

be held some  $30^{\circ}\text{--}50^{\circ}\text{C}$  ( $54^{\circ}\text{--}90^{\circ}\text{F}$ ) lower than if the metal is first tapped into a casting ladle, but on the other hand it suffers from the disadvantage that, as a thorough skimming of the metal cannot be done in the furnace, it is more difficult to avoid impurities, especially oxide, running into the mould. For this reason furnaces with fore-hearths or double hearths are now used in some instances, the impurities being held back in the melting hearth, and only the clean metal running into the fore-hearth or settling hearth.

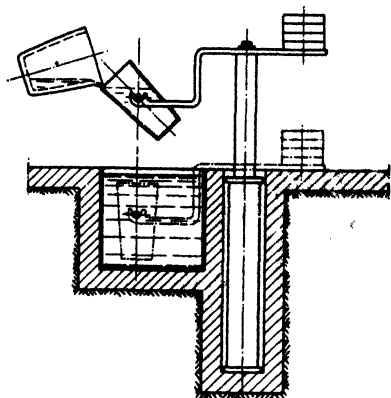


Fig. 133. Bucket casting (bag casting).

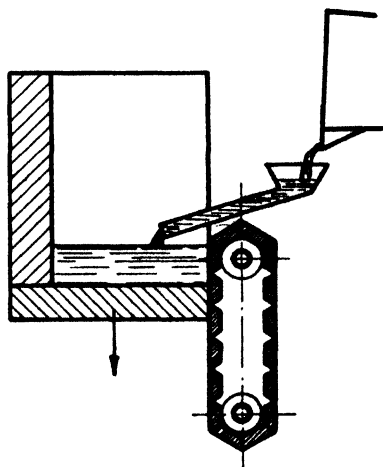


Fig. 134. Züblin casting process.

Investigations seeking to overcome segregation and coarse crystallisation by means of accelerated cooling led to the development of the "bag" or "bucket" casting process (Fig. 133) in which the metal is cast into a sheet steel mould about  $1/8$  inch thick, which is then lowered at a pre-set speed into cooling water. However, even under these conditions solidification proceeds from the outside to the centre, and as soon as the outermost layer of metal has become solid, this shrinks away from the sheet steel wall as it cools and forms an air-space, which considerably restricts the heat transfer. The "bucket" casting method for this reason gives mainly a finer crystal size without appreciably influencing the inverse segregations.

ZÜBLIN (Swiss Patent 112, 993) was the first to recognize that a different casting process was necessary to achieve this object. In place of the tilting chill mould, he employed a descending vertical mould with one side open, as shown in Fig. 134. The open narrow side is closed with movable metal plates as the filling of the mould proceeds. The rate of casting is so adjusted that it corresponds approximately to the rate of solidification, so that the depth of the liquid layer on top of the already solid metal remains steadily about 1 or 2 inches deep. In the old chill casting method, the flow of heat,

as shown in Fig. 135, is principally towards the sides, but in the ZÜBLIN process and even more so in the continuous or long casting process yet to be described, the heat is mainly conducted away vertically downwards, whereby the whole process of solidification is fundamentally altered.

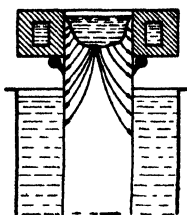
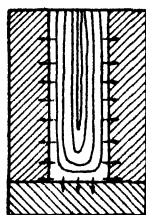


Fig. 135.

Heat flow and stages of solidification.

Left: chill block mould.

Right: continuous casting process.

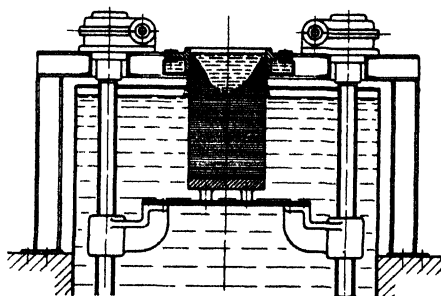


Fig. 136.

Continuous casting process — Zunckel.

Since the capacity of the ZÜBLIN mould is relatively limited, and the rate of heat extraction does not attain the optimum, casting processes have been further improved by other inventors, and continuous casting processes have been developed. In the "climbing" casting process, two shallow chills are placed one above another in succession, thus appearing to climb up the cast bar, whereby the bar travels continuously downwards in the form of a long column. In the now widely used "continuous casting" process or "long casting" process (Fig. 136), the process is still further



Fig. 137. Junghans/Rossi continuous casting machine with long cast billets in the foreground.

simplified, only a shallow collar a few inches deep being employed as a mould, from which the partly solid slowly moving bar slides out downwardly. The cooling of the mould and the resulting horizontal heat extraction from the portion of the bar inside it is so adjusted that a thin shell of metal, only sufficiently thick to hold the liquid remainder of the metal, is allowed to solidify in the mould, while the majority of the

heat extraction takes place in the vertical direction through the already solid lower part of the block or bar, by means of water sprayed direct on the exposed portion of the bar.

Fig. 137 shows a complete equipment for continuous casting by the JUNGHANS-ROSSI process, in which the mould moves downwards for one inch or so with the cast bar and with a uniform velocity and is then raised through the same distance about five times as rapidly, whereupon the downward motion is restarted. This casting process is characterised by a high

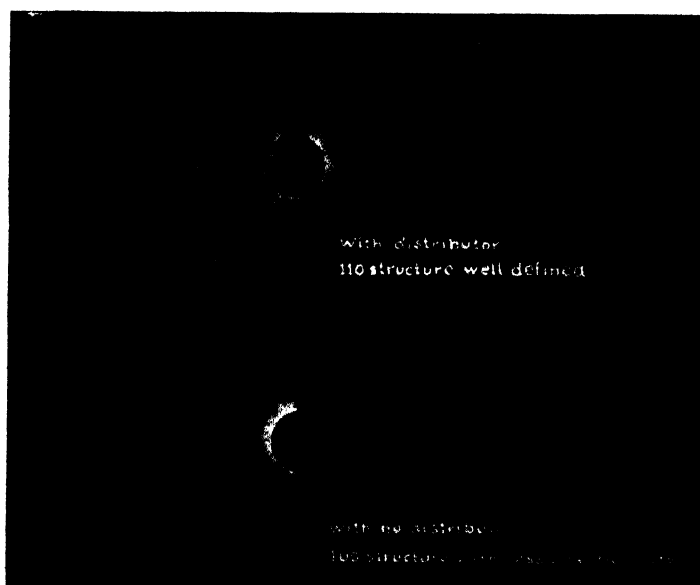


Fig. 138. X-ray diffraction patterns of continuous cast blocks cast by different methods.

rate of output. It is a true continuous process in which the metal coming down below is sawn off at intervals by a flying circular saw, so that casting can be carried on without interruption all day long, until the substitution of another alloy or shape of bar makes it necessary to close down. In the foreground can be seen the sawn billets.

The idea of these continuous casting processes is by no means new. The oldest patent on the subject was issued to LAING in 1843 and since then a large number of additional patents for both heavy and light metal bar casting<sup>1</sup> have been brought out prior to the industrial adoption of the process in 1936.

It is worthy of note that the method of casting has a clearly recognisable effect not only on the crystal structure and segregation of the aluminium, but also on the orientation of the crystals, as in the example shown in the

<sup>1</sup> HERMANN, *Aluminium-Arch.*, Vol. 16, 1940 and 1941 supplement.

X-ray diffraction photograph, Fig. 138, in which with one method of casting the aluminium crystals are oriented with 100 cube faces parallel to the casting axis, and with the other method 110 diagonal planes are parallel to the casting axis.

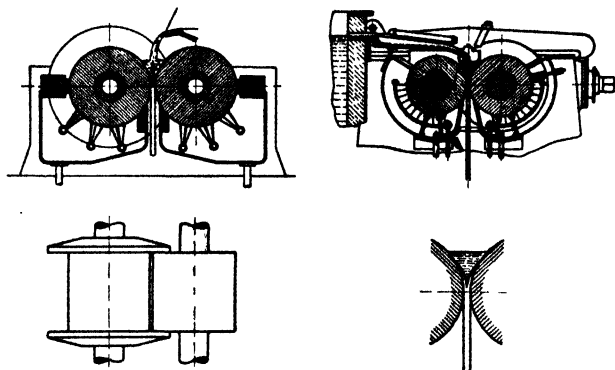


Fig. 139. Direct casting-rolling machines.  
Left: Bessemer 1857; Right: Hazelett 1932.

This difference of crystal orientation has an effect on "earing" in the deep drawing of sheets produced from such blocks (see p. 232). Recently, also, attempts have been made to influence the structure of the metal on solidification by means of high-frequency vibrations, applied either to the mould or to the molten metal contained in it.

In one of the recent proposals for continuous casting, the object is to produce a rolled plate direct from the molten metal. This idea was first described in a patent specification by BESSEMER in 1857. A practical appli-

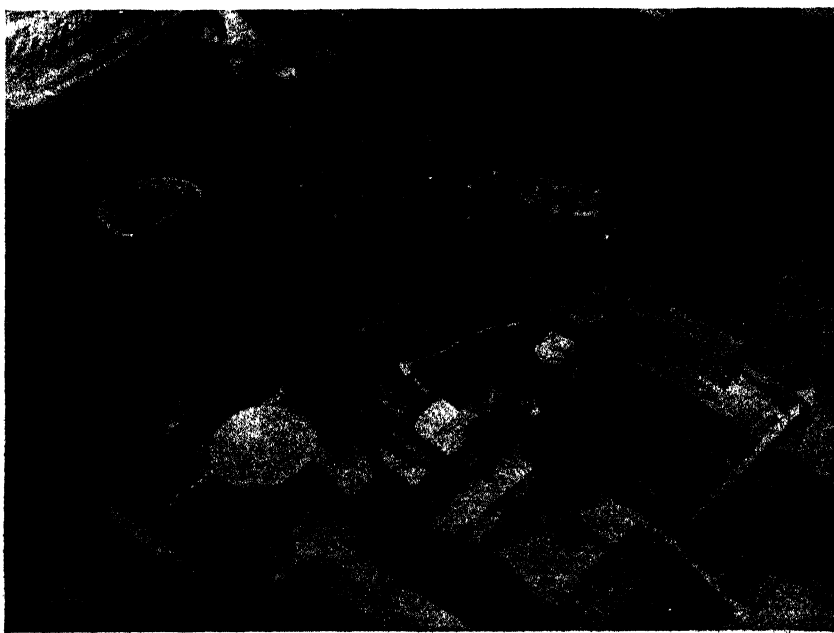


Fig. 140. Hazelett direct rolling machine.

cation was made by HAZELETT in 1932. Fig. 139 illustrates the principle and Fig. 140 an installation of this casting-rolling process. The material of the rolls can withstand the action of molten aluminium owing to its low melting point; on the other hand the surface quality of the rolled product is not always unexceptionable. There is a tendency for the oxide skin which forms on the surface of the molten aluminium to be drawn along by the rotating motion of the rolls. It might be possible to overcome this difficulty by the use of a non-oxidising protective atmosphere, for example, and if this is achieved, the direct rolling process seems to hold promise for cheap mass production. JUNGHANS has combined a hot rolling process with the continuous casting process, for which the cast block is cooled only to 400°-500°C (752°-932°F) and immediately after it has emerged from the continuous casting machine it enters a very powerful rolling mill which reduces its thickness by 50% in one pass.

TABLE 23

PROPERTIES OF MAGNESIUM, ALUMINIUM, CAST IRON, STEEL AND  
BRASS CASTINGS

	Magnesium	Aluminium	Cast iron	Steel	Brass
Specific gravity . . . . .	1.74	2.7	7.2	7.8	8.4
Melting point . . . . .	°C 650 °F 1202	658 1216	abt. 1250 „ 2280	abt. 1470 „ 2680	abt. 900 „ 1650
Specific heat 0°C (32°F) to melting point kcal/kg°C . .	0.27	0.25	0.19	0.19	0.12
BThU's/lb°F. . . . .	0.15	0.14	0.106	0.106	0.067
Latent heat of fusion kcal/kg	47	92	70	65	40
BThU's/lb. . . . .	85	166	126	117	72
Total heat in molten metal kcal/kg. . . . .	220	250	350	350	140
BThU's/lb. . . . .	400	450	630	630	250
Mechanical Properties					
a) Sand castings					
Tensile strength, tons/sq in. .	9—18	8—24	9—19	25—44	8—16
1000 lb./sq. in. . . . .	20—40	18—54	20—43	56—98	18—36
Elongation % . . . . .	1.5—5	0.5—9	1	8—20	3—10
b) Die castings					
Tensile strength tons/sq in. .	9—18	9—25	—	—	19—22
1000 lb./sq in. . . . .	20—40	20—56	—	—	43—50
Elongation % . . . . .	1.5—15	0.5—12	—	—	10—20
Young's modulus, tons/sq in.	2600	4300	5000	12700	6300
—2700	—5400	—9500	—14000	—7000	
million lb./sq in. . . . .	5.5—6.0	9.6—11.8	11.2—21	27—31	14—16
Relative price (aluminium cast- ings per lb. = 1)					
Per pound . . . . .	1.75	1	0.06	0.10	0.5
Per cubic inch . . . . .	0.11	0.1	0.016	0.029	0.16

## 4. THE PRODUCTION OF CASTINGS

a. *General considerations*

The physical properties of the light metals have to be taken into consideration for their correct application in the manufacture of castings.

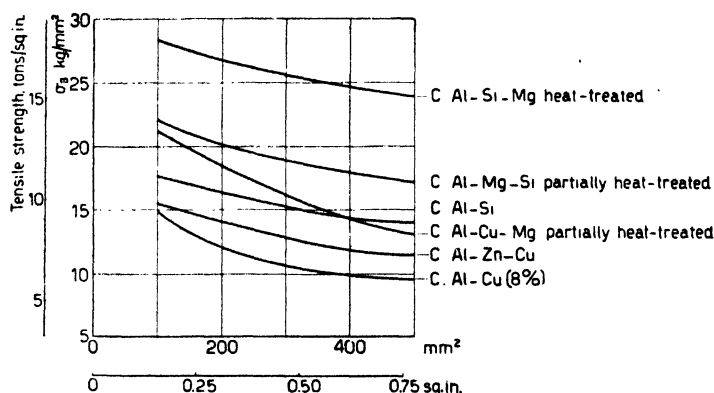


Fig. 141. (cast round rods tested) Wall thickness sensitivity of aluminium alloys.

A study of Table 23 shows a higher price for the light metals, as well as a lower modulus of elasticity. The higher price is discounted by the weight saving, but the lower modulus calls for increased moments of inertia. The unfavourable effect of increased wall thickness on the tensile strength (wall thickness sensitivity) can be seen in Fig. 141, and it is clear that an increase in the moment of inertia should certainly not be obtained by thickening up the walls. To confer equal stiffness on an aluminium rod as may exist on one of cast iron, its diameter must be increased by one third, and even so there is a weight saving of 40% for aluminium. When designing in light alloy, equal stiffness with a smaller consumption of material can be obtained by some additional bracing of the design by the use of more thin ribs. In comparison with cast iron, a 10% increase in volume of material is all that is necessary, and this gives a weight saving of 70%. Fig. 142 shows a crank-case cast in grey iron and in Silumin, the greater reinforcement of ribbing in the light alloy design being clearly visible. The designer must always bear in mind that a strong reason for the use of light alloys is weight saving, and he must therefore apply a knowledge of the principles of design in light alloys in every case. Compared with the modulus of elasticity of 4400 tons (9.8 million lbs) per sq. inch for aluminium, that of magnesium is lower at 2600 (5.8 million), so that in spite of its smaller specific gravity, magnesium usually cannot be substituted with advantage.

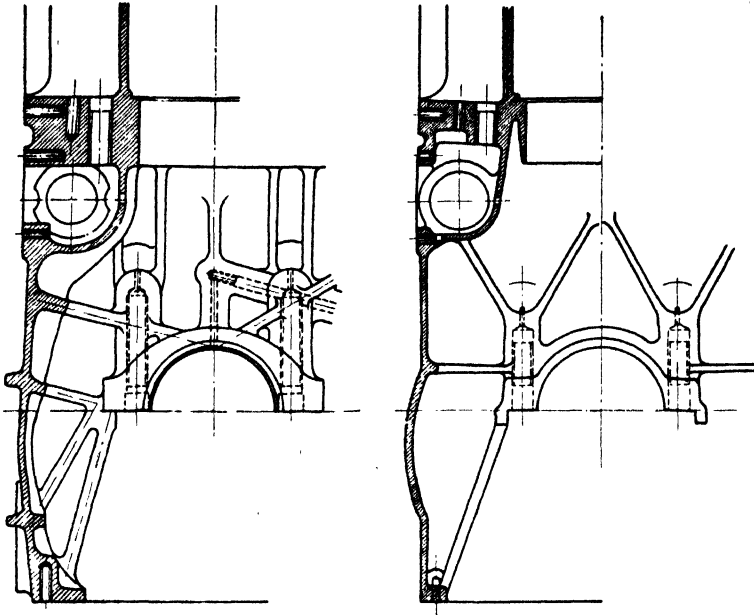


Fig. 142. Crank-case; Cast in Silumin (C: Al-12Si) left, cast iron right (Saurer).

In the selection of the alloy, its price per pound should not be regarded as necessarily of the first importance, but more frequently the physical properties of tensile strength, proof stress, elongation, impact strength and specific gravity are collectively given the greater consideration. Careful calculation frequently shows that the most expensive alloy gives the most economical casting. In addition the conditions of service for the casting, whether statically or dynamically stressed, must be taken into consideration especially in determining the condition of heat-treatment to be used for

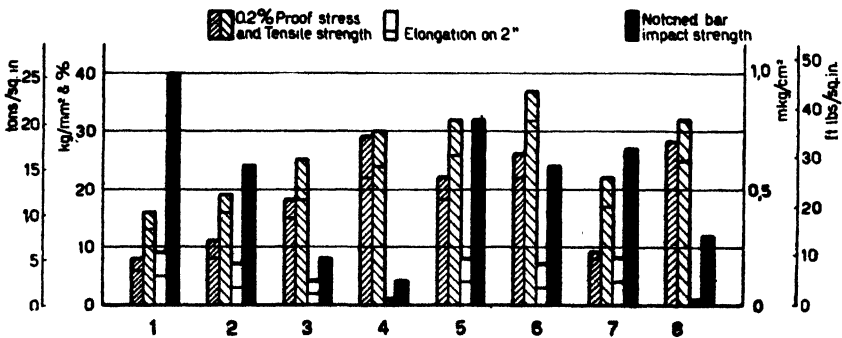


Fig. 143. Variation of properties in different cast alloys with different compositions and heat-treatments.

- |                                      |                                   |
|--------------------------------------|-----------------------------------|
| 1 = Peraluman 3 (C: Al-3Mg).         | 5 = Alufont 3A (C: Al-Cu-Ti (A)). |
| 2 = Peraluman 5 (C: Al-5Mg).         | 6 = Alufont 3B (C: Al-Cu-Ti (B)). |
| 3 = Anticorodal A (C: Al-Si-Mg (A)). | 7 = Silafont 1 (C: Al-12Si).      |
| 4 = Anticorodal B (C: Al-Si-Mg (B)). | 8 = Silafont 2 (C: Al-12Si-Mg).   |





Fig. 144. Cast aluminium alloy casing for a three-stage turbo-compressor (Swiss Locomotive and Machine Works, Winterthur, Switzerland).

the alloy. Maximum precipitation treatment always impairs the elongation and impact strength, so that the semi-hardened condition is frequently to be preferred on account of the higher elongation and impact strength that accompanies it, as with Anticorodal (C: Al-Si-Mg) and Alufont (C: Al-Cu-Ti) for example (Fig. 143). An interesting example of a casting is the turbo-compressor casing shown in Fig. 144. In this the stiffeners act also as cooling

fins, and being cast flush in the casing, the maximum stiffness combined with the smallest amount of material and overall size are obtained.

The high solidification shrinkage of the aluminium alloys makes it of special importance to have uniform thickness of section as far as possible and that change of section, if unavoidable, should be gradual. Unavoidable concentrations of mass in the casting require the provision of risers above them in the mould or, if this cannot be arranged, stronger cooling by chills or similar measures.

The different alloy constituents affect the nature of the solidification,

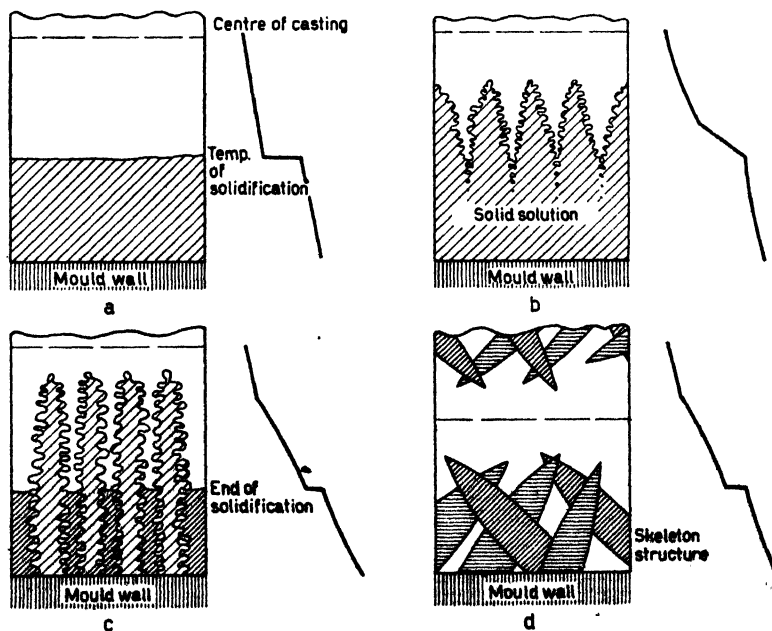


Fig. 145. Effect of alloy composition on habit of solidification.

Pure metal or eutectic alloy.      b Solid solution alloy.      c Alloy with solid solution and eutectic.

as shown in Fig. 145. Pure metals and eutectic alloys solidify uniformly, more or less in a plane advancing from the mould wall to the interior (a), whereas those alloys which have primary crystals and smaller proportions of eutectic undergo a process of solidification as depicted in (c), the primary crystals advance first through the melt and the interstices are eventually filled with the eutectic which solidifies at a lower temperature. True solid solutions solidify with a dendritic structure (b), impurities and voids often being concentrated at the crystal boundaries. The most undesirable block structure is the acicular or needle-like structure (d), also known as the skeleton structure. This occurs with iron contents over 1%. The eutectic-structure alloys have the best mould-filling or running qualities and for this reason allow the production of the smallest wall thicknesses.

In regard to the mechanical properties of castings, not only the pouring temperature but also the superheating temperature of the metal exert a powerful effect. The hotter the metal used for casting, the slower the solidification, the strength being thereby affected.

Aluminium alloys can be cast equally well in sand and metal moulds. With metal moulds there is a distinction between gravity die casting in which the metal fills the mould under a hydrostatic head equal to the height of the gate, and pressure die casting in which the metal is forced into the mould under intensified pressure. In air injection die casting, compressed air is used to inject the metal under pressure; with "cold chamber" machines in which a plunger is forced into semi-solidified metal, the process is called press-casting, while if in such machines the molten metal is introduced in an asbestos cup or bag into the pressure chamber and is then

TABLE 24

## COMPARISON OF THE STRENGTH OF SAND AND DIE CASTINGS

Alloy Type	Alloy	Average tensile strength				Strength of sand castings as percentage of strength of die castings
		Sand castings		Die castings		
		Tons/sq. in.	1000 lbs. per sq. in.	Tons/sq. in.	1000 lbs. per sq. in.	
C: Al-Si	Silafont 1 as cast	11	25	13	29	85%
C: Al-Si-Mg	Silafont 2 and 3 as cast . . . .	12	26	15	34	77%
C: Al-Si-Mg	Silafont 2 and 3 heat-treated .	17	38	18	41	93%
C: Al-Cu-Ni	Y alloy as cast .	11	25	15	32	76%
C: Al-Cu-Ni	Y alloy heat-treated . . . .	16	36	17	38	93%
C: Al-Cu-Ti	Alufont semi-hard . . . . .	18	41	23	51	83%

pressed into the die with a plunger, the process is called pre-casting.

The decision as to which type of casting to adopt involves several considerations. Owing to their more rapid and fine-grained solidification, die castings always have superior strength to sand castings (See Table 24). On the other hand the total cost of a metal mould is much higher than that of the pattern for a sand mould. Against this, the cost of the casting dies per pound of castings, as the same mould is used over and over again, is lower than the mould cost in sand casting, in which a new mould must be made for every casting. The simpler the mould, the smaller is the number of castings off at which the cost of production of die castings including cost of the moulds, becomes equal to that of sand castings.

The higher strength and dimensional accuracy of die castings permit additional weight-saving and render the advantages of their use still more pronounced. In general, the following advantages can be claimed for die castings:

- |                                 |   |
|---------------------------------|---|
| 1. Higher strength              | 6. Lower casting cost though with higher initial mould cost |
| 2. Less weight                  | 7. Smaller weight of runners and risers                     |
| 3. Superior appearance          | 8. Lower overhead charges                                   |
| 4. Greater dimensional accuracy | 9. Given the dies, a shorter delivery time                  |
| 5. Lower cost of inspection     |   |

Fig. 146 shows side by side the casting arrangement for a die cast and sand cast luggage rack bracket with gates and risers shown in position. With this piece, for equal strength the weight in Silumin Gamma die-cast amounts to 2 pounds and in the same alloy sand cast 2.5 pounds, a saving



Fig. 146.

Castings of luggage rack bracket —  
sand cast and gravity die cast.

of 20 % in weight for the die casting, while the weight of gates and risers is 10 pounds for the sand casting, which is twice that for the die casting. In a medium sized aluminium foundry, the average costs for sand castings are nearly fifty per cent higher than for die castings, this being due mainly to the higher incidence of mould and overhead costs. To be able to take full advantage of die castings, it is essential that the designer should collaborate with the foundryman and should examine the possibilities of die castings as widely as possible.

There are different methods used for detecting casting defects. The

castings for instance may be struck with a pointed hammer to enable porous places to be detected. Besides these, shrinkage cracks can be made visible with a hot dip test in which the casting is dipped in hot oil and after removal of oil from its surface, it is coated over with whitewash. After a short time, yellow streaks on the whitewash coating will appear wherever oil has exuded from pores or cracks in the casting. Recently a solution of 2% ammonium acetate, 15% pot. bichromate and 83% water has been preferred to oil. The time of the hot dip is  $\frac{1}{2}$  hour at 70 to 80°C (158—176°F). After washing in cold water and finally in hot, chromate stains are formed at any pores and shrinkage cracks in 1 to 4 hours.

#### b. Sand casting

In aluminium sand casting, the low specific gravity of the metal and its high affinity for water vapour influence the moulding practice. The low specific gravity results in a hydrostatic pressure in the mould only one third as great as for cast iron, which affects the mould-filling propensities and the venting. For this reason it is very necessary to ensure in aluminium moulding practice that the mould is filled uniformly from the lowest point, and that the gases expanded by the heat are provided with an uninterrupted passage out of the mould. As venting cannot always be arranged by risers, the moulding sand must be of a high permeability. As aluminium is generally cast in green-sand moulds, the moisture content of the sand must be kept as low as possible, in order that an undesirable amount of steam should not be generated by the hot stream of metal as it enters the mould. A good moulding sand shows satisfactory moulding qualities and cohesion with 7% of moisture. This water content must always be maintained by proper sand control. In large moulds, nevertheless, an excessive generation of steam cannot be avoided. It is therefore the com-

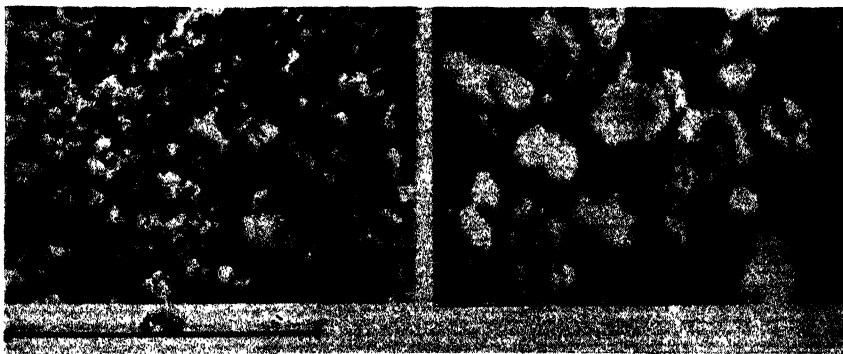


Fig. 147. Grain size of different moulding sands.

mon practice to skin dry the moulds with a flame before casting. For this, a benzine or petrol blow lamp, or a gas torch can be used, or electrically heated air. After skin drying, the mould is closed without loss of time and cast, since otherwise the dry skin of the sand which is only a few sixteenths of an inch deep, absorbs moisture again from the underlying sand.

The permeability of the moulding sand depends principally on the uniformity of its grain-size and on the grain shape. Fig. 147 shows a uniformly coarse sand and also an uneven mixture. If the sand is composed

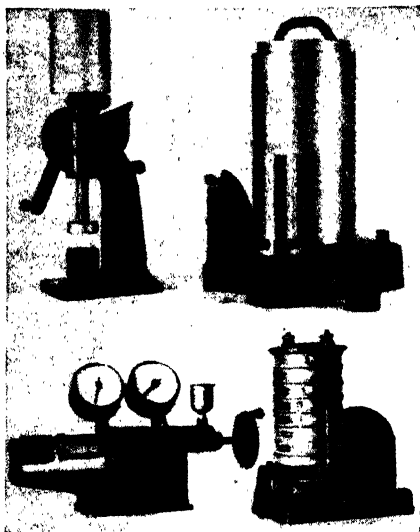


Fig. 148. Sand testing apparatus  
(George Fischer Ltd.,  
Schaffhausen, Switzerland).

of grains of a large range of sizes, the fine grains pack the spaces between the large grains and reduce the permeability to gases. AULICH distinguishes five grades of grain-size; over 0.3 mm, 0.3 to 0.2, 0.2 to 0.09, 0.09 to 0.05, and less than 0.05 mm. A sand with over 40% of grains under 0.09 mm is generally designated fine grained, with more than 45% 0.2 to 0.09 mm medium grained, and with more than 30% over 0.2 mm coarse grained. Although this grading is not altogether satisfactory, it has been widely adopted. For aluminium foundry work, only medium and coarse grained sands are used and the percentage of grains under 0.09 mm should be as low as possible. The facing sand should however not be too

coarse, else the surface of the casting will have a rough appearance. Beside the sizing test on the sand, the clay content must be watched, as this affects not only the bonding power and strength but also the permeability. A good aluminium foundry sand has 10 to 15% total clay stuff. Additions of powdered coal are to be avoided as impairing the permeability. A good facing sand would contain about 20% of grains size 0.3 to 0.2 mm and 60% 0.2 to 0.09 mm, while a good backing sand would in general be coarser grained. By means of the sand testing apparatus shown in Fig. 148 the grain-size analysis and compressive strength, as well as the permeability to gases in cc/min for a standard test sample may be determined. With regard to permeability, an ideal facing sand would show 90cc/min, while a backing sand with 65% grains on 0.3 mm would show over 300cc/min.

Moulds for magnesium castings are, in consequence of the great affinity of molten magnesium for water vapour, either completely baked or are

made with an addition of 3 to 4% of sulphur and the same proportion of boric acid. Sometimes ammonium oxalate is also added. Since these additions are gradually lost when the sand is continually used, make up additions of 1% are added at each time of use. In America, diethylene-glycol and ammonium fluoride are sometimes used as additions. All these additions generate a protective atmosphere in the mould which inhibits the reaction of molten magnesium with water vapour. With the same object, sulphur dioxide gas is usually led into the mould before casting, while during casting sulphur is sprinkled on the molten metal. Apart from these preventive measures, the moulding sand for magnesium must have a considerably higher permeability than a sand for aluminium if castings free from defects are to be produced. In general, magnesium castings are inclined to show higher porosity than aluminium.

For cores, special mixtures of old and new moulding sands mixed with binders are used (Table 25), though sometimes ordinary facing sand is used.

TABLE 25

## CORE SAND MIXTURES

	With pitch binder		With oil binder	With dextrin binder
Old sand . . . . .	60%	78.5% <sup>1</sup>	50 %	55%
New sand . . . . .	39%	20 %	48.5%	44%
Binder . . . . .	1%	1.5%	1.5%	1%

<sup>1</sup> Silica sand

Since natural moulding sands entirely suitable for aluminium castings are not altogether easy to find, increasing use is being made of synthetic sands artificially compounded of silica sand, clay binder and Bentonite. By this means perfectly suitable aluminium moulding sands can be obtained from convenient sources.

(i) *Patterns*

The quality of the pattern is of special importance seeing that weight saving is a reason for the use of aluminium. Only with an accurate and carefully made pattern can a casting of accurate dimensions be guaranteed. In the first place, the pattern must have sufficient draft or taper so that it may be drawn from the sand without excessive rapping and without damaging the mould. All interior angles must be well filleted and at the

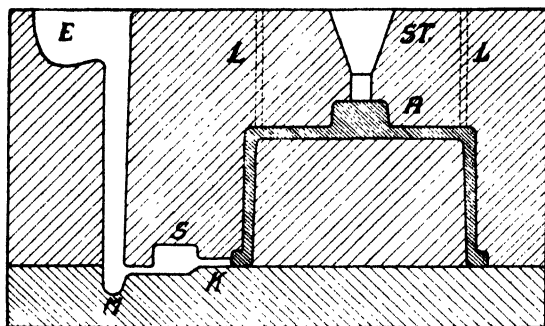


Fig. 149. Moulding and gating practice for a hollow cylindrical casting.

junctions of thick and thin sections the change of size should be made gradual. Drawbacks and undercuts are to be avoided as far as possible and core prints should be on the large side, as the cores are frequently made without core irons. Careful making of the pattern and core boxes not only increases

the accuracy of the casting and limits any excess of weight, but contributes also to the reduction of moulding cost. Even with quantities of 20 to 50 castings off one pattern, the making of a metal pattern pays for itself, and aluminium is a very good material for the pattern.

#### (ii) Moulding practice for sand castings

The correct arrangement of the casting in the mould, the type of gate, and the placing of risers and chills have much influence on the quality of the casting. It is generally found that the upper portions of a casting in the mould are more liable than the lower to have some casting defects such as porosity and inclusion of dross arising from the oxide skin; thus any surfaces that will have to be machined are best arranged in the lower portion of the mould. Fig. 149 shows the method of making the mould for a simple casting. The metal is poured into a pouring basin E and passes down the gate or sprue through a runner into a skimming gate S, then enters the casting by the in-gate K which will have been cut in the sand. M is a sump in the gate for the purpose of trapping sand washed down in the pouring of the metal. The in-gate should be taken into the mould at its lowest point. The cross-sectional sizes of the down-gate, runners, and in-gate must be proportioned so that the in-gate can be kept full of molten metal all the time. This can be achieved by making the total cross-sectional area of the in-gates not greater than the total for the runners, and this not greater in the section than the down-gate or sprue. If two runners are taken from the

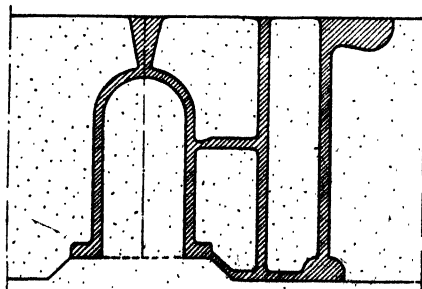


Fig. 150. Gating practice for deep castings.

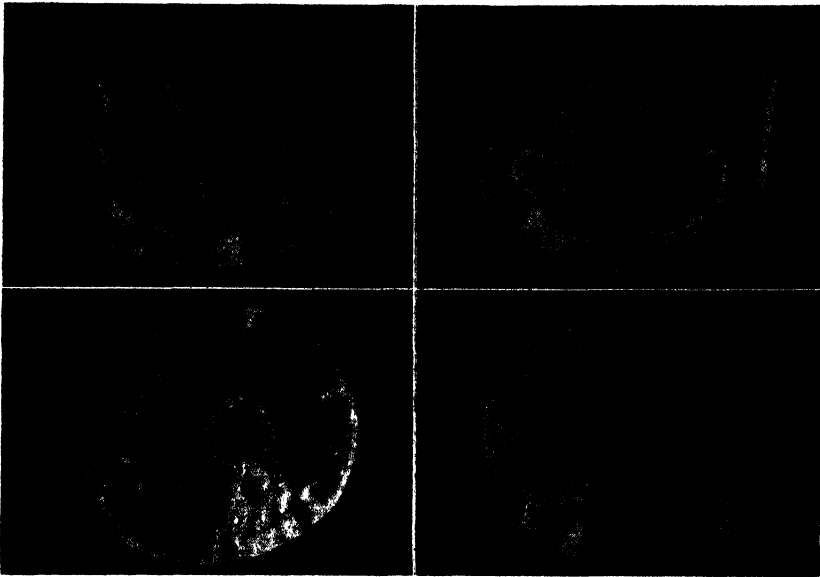


Fig. 151. Arrangement of runners, risers and chills for a complicated casting (Trilex wheel).

down-gate, the area of the cross-section of each runner should be half that of the down-gate. The down-gate is generally made either round or square in section, the runner rectangular with high sides, and the in-gate a flat rectangle. With very deep castings, in-gates at different heights are necessary, which must be supplied from a special riser (Fig. 150). It is also to be noted that the fluidity of various alloys may be somewhat different. Silumin is a very fluid alloy with good mould-filling characteristics. The Al-Zn-Cu alloy is distinctly less fluid and, for a similar casting, this alloy calls for larger sections of runners and gates to be used.

Large and complicated castings are gated at several points. For this it is a

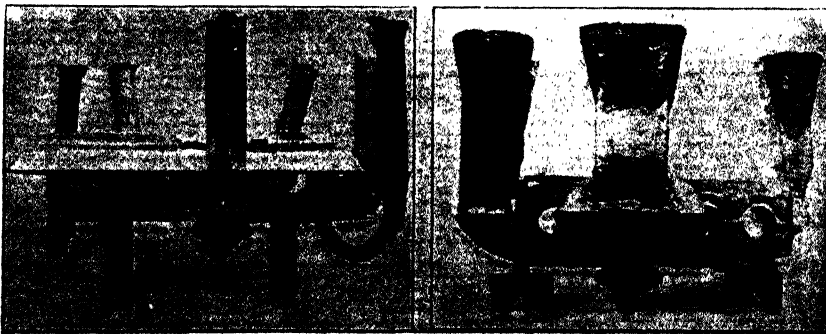


Fig. 152. Size of risers for different alloys (High Duty Alloys).



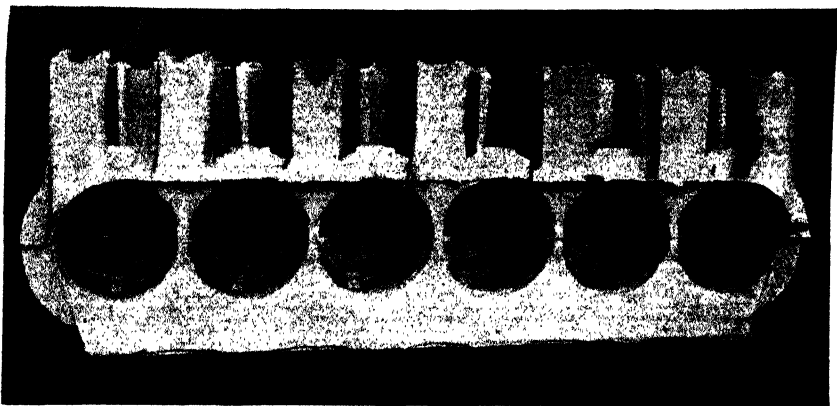


Fig. 153. Cylinder block with risers (Schweizerische Lokomotiv- und Maschinenfabrik).

frequent practice to have ring gates consisting of one or more ring runners completely round the casting, delivering into the casting by several in-gates.

In Fig. 151 is shown the arrangement of the mould for casting a "Trilex" wheel in Alufont 3 (C: Al-Cu-Ti alloy). The metal is poured down two down-gates and enters the runners, from each of which three in-gates enter the mould, chills being provided with the object of increasing the strength of the casting. The increased use of chills permits the replacement of the small risers by air vents as shown on the right, whereby the weight of metal used in risers is reduced from 40 to 32 pounds. In both cases the gate has a weight of 7 pounds. The weight of the fettled casting is 34 pounds, while that of the casting with gates and risers was 72 or 80 pounds.



Fig. 154. Turbogenerator casings with ventilating channels (Maschinenfabrik Oerlikon, Switzerland).  
A Silumin casting  
(C: Al-12Si).

Fig. 152 shows how the volume of the risers must be varied to suit the alloy used; on the left the low-shrinkage German high-percentage alloy with 12% Zn and 2% Cu; on the right the low-percentage alloy RR50 with 1.3% Cu, 2.2% Si, 1% Ni, 1% Fe, 0.1% Mg which owing to its greater solidification shrinkage requires at least four times the volume of risers to produce a casting free from defects. On the left picture the horn gates can be clearly seen.

Risers are provided for the purpose of venting the mould and preventing cavities, sinks or draws. In simple moulds, sufficient venting is afforded by a riser on the highest point of the casting, but for complicated moulds, all thicker sections should be provided with risers as far as possible,



Fig. 155. Propeller fan with riveted-on radial blades. Casting in Silumin (C: Al-12Si); blades in Anticorodal (Al-Si-Mg) sheet. (Maschinenfabrik Oerlikon).

as in Fig. 153. If the mould does not allow risers to be applied, artificial cooling of the thicker sections must be provided by the use of chills, so that the metal does not remain molten at these places for too long. Chills are also provided at all places where specially high strength is required. It is thus advisable for the designer to indicate on the drawings, not only the surfaces to be machined, but also to point out the high-stressed regions of the casting, so that the foundryman can bring about increased strength at these places by the use of chills.

In many cases, the non-magnetic property of aluminium is of importance. Fig. 154 shows a turbogenerator end cover of about 6 feet diameter with ventilating ducts cast in Silumin, and Fig. 155 the axial-flow fan for the rotor, also cast in Silumin. To save weight, the radial ventilating vanes in the same part are built up of Anticorodal (Al-Si-Mg) sheets riveted to the casting. Instead of riveting, such sheet parts are often cast integral.

Aluminium is particularly well suited to the founding of statuary. As already mentioned, the oldest example of this is the statue of Eros, placed in Piccadilly Circus, London, in the year 1893. Fig. 156 shows a similar statue at the canton library in Lugano. The moulding and casting practice for aluminium statuary is similar to that for bronze, no special measures being necessary for aluminium.

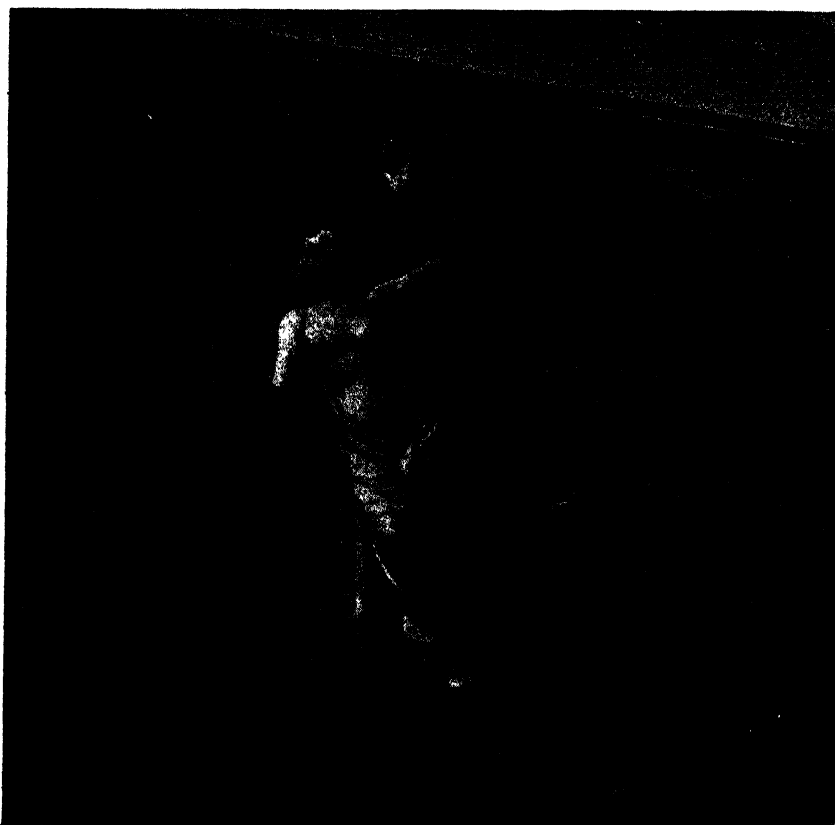


Fig. 156. Statue on the canton library at Lugano, cast in Peraluman (C: Al-Mg)  
Sculptor: Remo Rossi ; Founder: Rüetschi A.G., Aarau, Switzerland.)

Fig. 157 shows a view in a modern aluminium foundry. In the foreground is the roller conveyor on which the moulds are closed, cast, and knocked out over a grid. The sand falling through the grid goes to a sand conditioning plant and then up an elevator and on a belt conveyor back to the three sand hoppers which show light coloured against the background, beneath which the moulding machines are situated. Fig. 158 shows the pouring of a large aluminium casting. The picture gives a good idea of the size attained by aluminium castings at the present day, and shows the large number of risers which have to be provided on a large casting.

### c. Gravity die casting<sup>1</sup>

In sand casting, the mould is destroyed in knocking out the casting, whereas in die casting, permanent metal moulds are used, and the per-

<sup>1</sup> Or permanent mould casting (U.S.A.).



Fig. 157. View in Renault sand foundry.

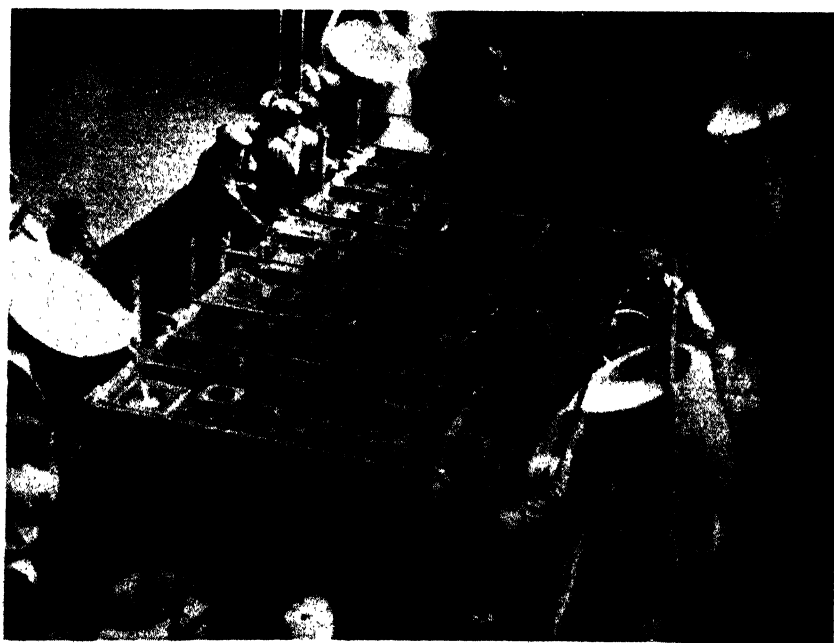


Fig. 158. Casting of a heavy piece in aluminium alloy (Aluminum Company of America).

manent mould must be so constructed that the casting complete with runners and risers can be removed from it. Again sand moulds are permeable to air, but metal moulds are not, so that particular attention must be paid to the venting of such moulds. These characteristics of permanent moulds indicate the greater difficulties involved in the die casting process, which are only surmountable in the case of relatively simple shapes of casting. For this reason, consultation by the designer with the die casting or permanent mould specialist is indispensable, in order that the advantages of the die-casting process from both the commercial and the technical aspects may be correctly evaluated. Fig. 159 shows the crystalline structure of the same alloy in a sand casting, a gravity die or "permanent mould" casting, and a pressure die casting.

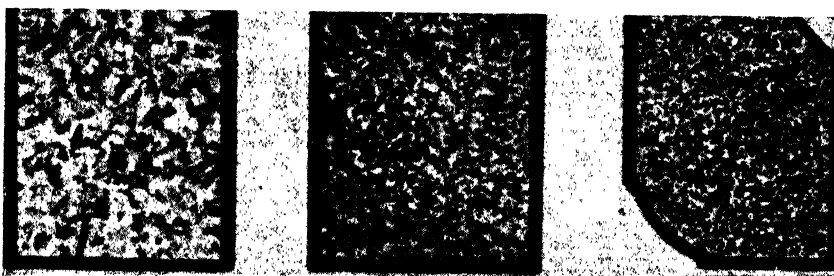


Fig. 159. Grain size of sand, gravity die, and pressure die castings, photomicrographs.

A sand mould has a certain amount of "give", and does not seriously restrict the contraction of the casting during solidification, but the metal mould is quite rigid and this presents an additional difficulty. For this reason, the alloys best suited to die casting are those with the lowest possible contraction, such as Silumin. In sand casting an accelerated rate of cooling in certain places is obtained by the insertion of chills, while in die casting the rate of cooling can be retarded by heat-insulating mould dressings applied internally, or by increase of the mould temperature. To obtain more rapid chilling, the dressing may be locally removed, copper inserts can be fitted in selected places in the mould, or cooling ribs be incorporated, and on the other hand a locally increased working temperature may be obtained by the local use of an insulating dressing or by local heating with gas flames. A mould dressing suitable for such use is composed of a fine mixture of china clay in water glass and water. This can be applied by a spray pistol or by a paint brush to the warm mould at a temperature of about  $160^{\circ}\text{C}$  ( $320^{\circ}\text{F}$ ).

### (i) Construction of moulds for gravity die castings

The permanent moulds for gravity die casting are generally made of a pearlitic cast iron, a suitable composition being total carbon 3 to 3.5% (including 0.4 to 0.5% combined carbon), silicon 1.6 to 2%, manganese 0.8 to 0.5%, phosphorus 0.5%, sulphur 0.05% max. Additions are often

used of chromium 0.6%, molybdenum 0.4% and nickel 0.2%. To prevent distortion of the moulds in use, they are annealed at 800 to 900°C (1472-1652°F) before being put to work. The venting of the moulds is provided for principally through the risers and through the parting joint of the mould, on which the risers and gates must also be located. The mould should be arranged so that as far as possible horizontal surfaces are avoided. If additional venting is needed, the joint may be rebated to a clearance of about .004 to .008 inch, or the mould may be drilled from the exterior and the holes be filled with pegs with

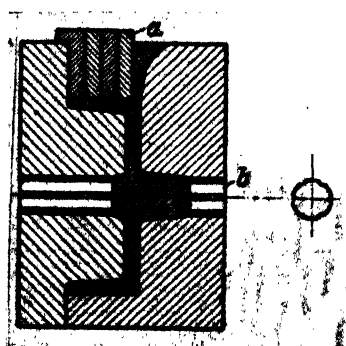


Fig. 160.

Venting of gravity die casting mould.

grooves about .010 inch deep milled in them, giving small channels along which the air can escape, Fig. 160,b.

The arrangement of the gate or gates is generally as for sand casting. The metal should enter the mould with as little turbulence as possible. Fig. 161 shows the different types of gate generally used for permanent moulds, the two examples of gates entering from above only being recommended for small castings when the mould can be sharply tilted at the commencement of the pour and tilted gradually back to the upright position as it fills. The so called swan neck gate as shown also is much used for casting pistons with the object of keeping back the oxide scum.

### (ii) Cores

For gravity die-casting dies, the cores are generally made of steel. Carbon steel is used for plain cores, but for complicated cores a chrome vanadium steel with 2.5% Cr and 0.2% V is

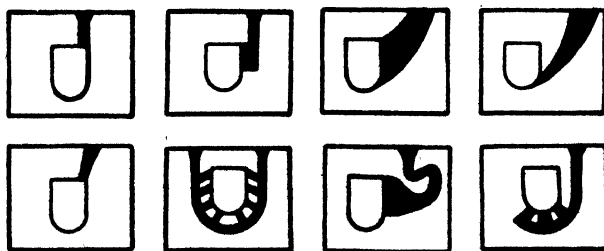


Fig. 161. Different methods of gating permanent moulds for gravity die casting, after Dr. Irrmann.

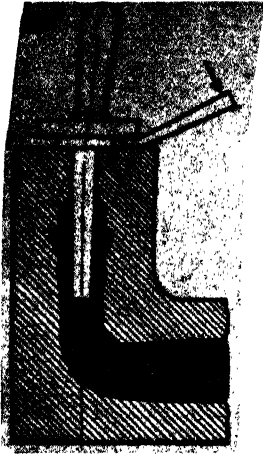


Fig. 162. Arrangement of core in gravity die.

used. To permit the cores to be withdrawn from the casting, they are given a taper or draft of at least 1 or 2 %. The greater the draft, the more easily they can be pulled out. In simple moulds, the cores, as shown in Fig. 162 are provided with a collar under which a pinch bar can be inserted to ease them out. The length of the cores is made proportional to the diameter. Thin cores have a maximum length of 4 times the diameter, while cores over 5/8 inch diameter may have a length equal to 8 times the diameter.

For pulling cores, a mechanical means is



Fig. 163. Simple permanent moulds for gravity die castings with eccentrics for drawing cores.

frequently provided. This may either take the form of a lever and eccentric as shown in Fig. 163, or with larger moulds, cranks or hydraulic core pulls, as shown in the example of a piston casting machine (Fig. 164), used in the Chrysler foundry. A simple mechanical gravity die-casting mould is shown in Fig. 165, in which one of the mould halves is crank actuated. The whole casting machine can be swung on a horizontal axis, so that the gate can be



Fig. 164 Mechanical permanent mould for pistons, Chrysler.

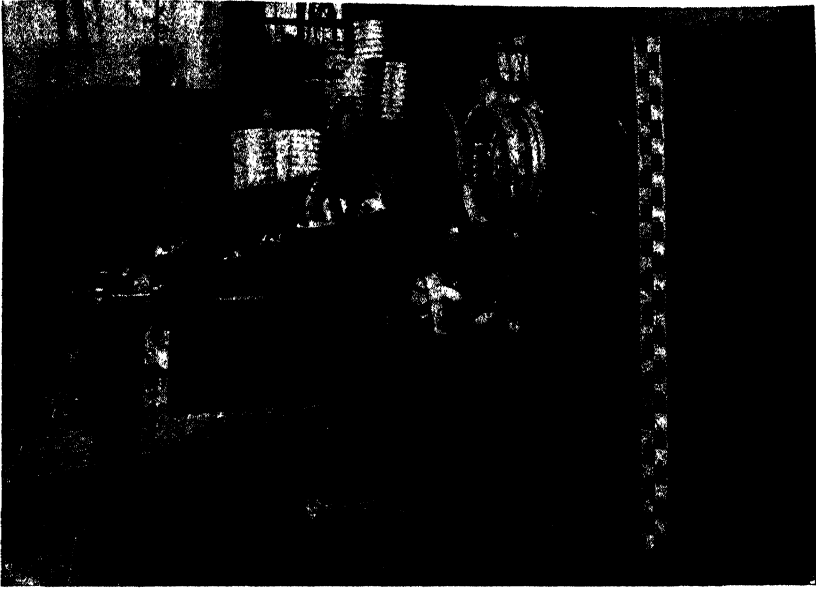


Fig. 165. Universal hand operated gravity die casting machine for permanent moulds.

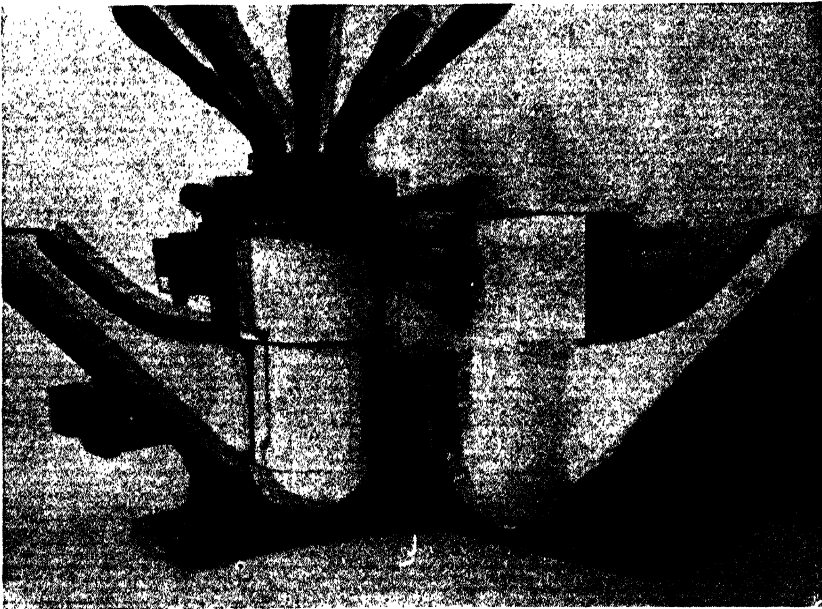


Fig. 166. Permanent mould with sectional core for gravity die casting of lamp bases.



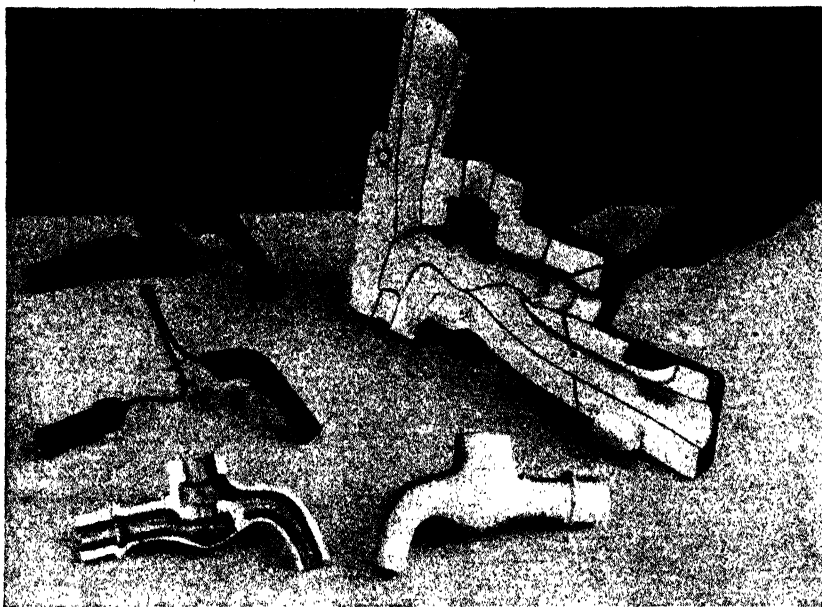


Fig. 167. Permanent mould with sand core.

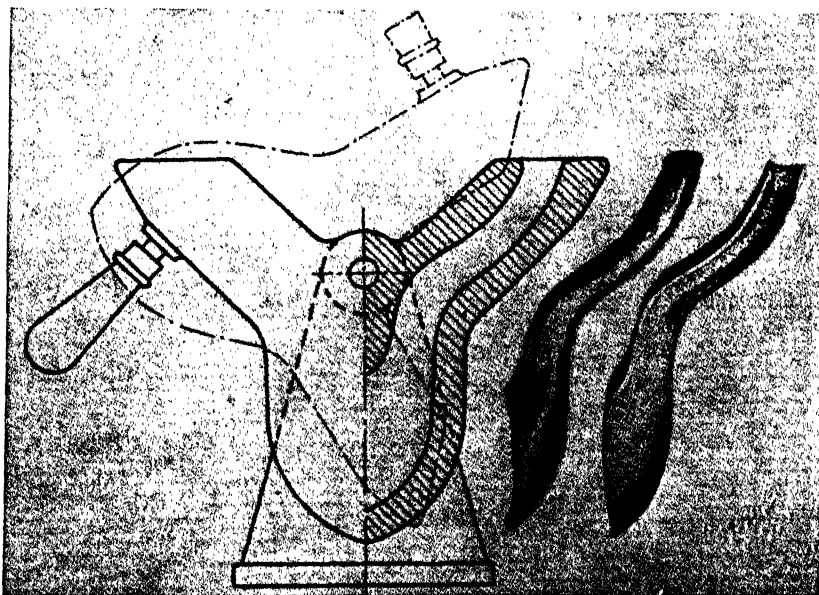


Fig. 168. Slush casting mould.

brought to the correct inclination for pouring. Fig. 166 shows a gravity mould for casting lamp bases, in which the vents are visible in the parting surface and in the five-part core.

For very complicated cores, sand cores are frequently used instead of metal, as shown in the water taps illustrated in Fig. 167. In this mould there are cooling pins for heavily chilling the valve seats as well as two small chills in the sand cores for a similar purpose.

### (iii) *Slush casting*

For cheap hollow articles, an internal core is frequently dispensed with. If a eutectic alloy is used, it is possible to obtain a hollow casting by tipping the mould and pouring out the still liquid metal after a thin layer has solidified against the mould walls. In Fig. 168 is shown such a mould for casting teapot spouts. The mould is made symmetrically double so that two spouts may be cast at one pour. On the right of the mould can be seen a casting cut open, showing the interior solidification surface of the casting.

### d. *Pressure die casting*

#### (i) *Pressure die casting machines*

A further development of gravity die casting (in which the metal fills the mould under its own head) leads to pressure die casting, in which the metal is injected into the mould under an artificially increased pressure. This casting process was originally developed for low melting point alloys, as used in printing for instance. DOEHLER was the first to develop a pressure die casting machine for aluminium in 1918. A major difficulty that did not exist with previous metals was that molten aluminium attacked iron vessels. The necessary hydraulic pressure could not therefore be satisfactorily obtained by means of a plunger in a metal cylinder held at the casting temperature. The higher melting temperature of aluminium of about  $700^{\circ}\text{C}$  ( $1292^{\circ}\text{F}$ ) determines the working temperature of the pressure vessel.

The aluminium air-pressure die casting machine as shown in Fig. 169 overcomes the difficulty by the adoption of a cast iron melting pot C, into which dips another cast iron pressure vessel or "goose neck" B, the mouth of which can be submerged below the surface

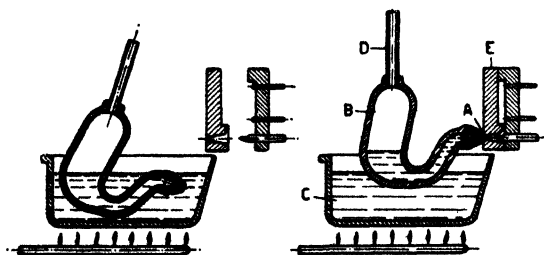


Fig. 169. Arrangement of compressed air pressure die casting machine.

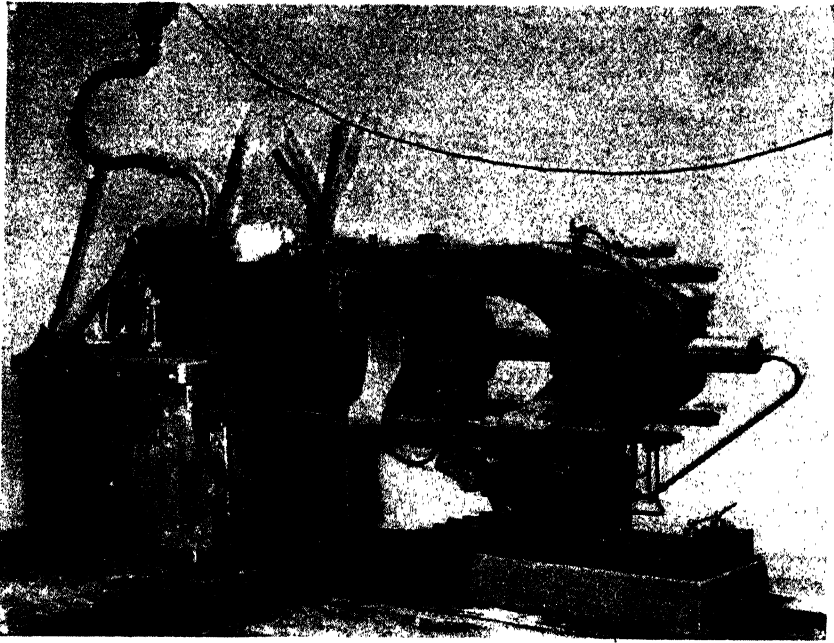


Fig. 170. Pressure die casting machine — Injecta A.G., Teufenthal.

of the molten metal. In the position for casting, the mouth of the goose neck engages with the front half of the die E, and compressed air at 300 to 700 lbs per sq. inch supplied through the pipe D injects the molten metal into the mould. A disadvantage of this type of machine is the unavoidable absorption of iron to the extent of 1 to 2%. Fig. 170 shows a medium sized die casting machine, on the left of which can be seen the melting pot covered with a hood, with the compressed air supply pipe. The opening and closing of this machine is done by hydraulic actuation, the valve being hand operated. For mass production, fully automatic machines are now used, of which an example is illustrated in Fig. 171. In these, the die cavity can be arranged for vacuum, whereby the difficulty of venting the mould is overcome and a die casting of superior soundness is obtained. The castings ejected from the mould after each shot collect in the vacuum chamber and the vacuum is released at intervals and the pieces are removed.

As the injection vessel or goose neck must be held at the casting temperature, the above type of machine is known as a hot chamber machine. In recent years cold chamber machines, also called press casting machines, have been developed (Fig. 172). In such a machine, the alloy charge 4, which should have a considerable solidification range, is poured into the pressure chamber 3 in a condition of incipient solidification. Immediately

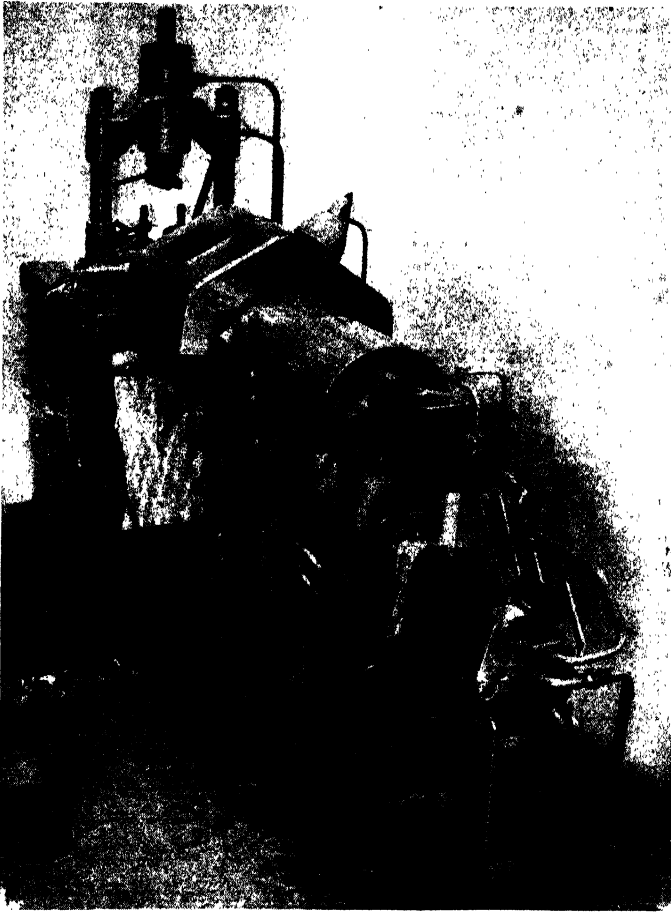


Fig. 171.

Fully automatic pressure die casting machine (Injecta A.G., Teufenthal, Switzerland).

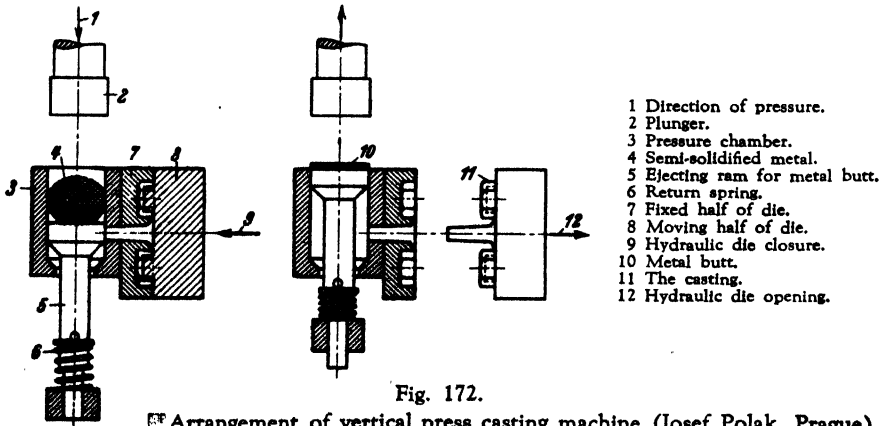


Fig. 172.

Arrangement of vertical press casting machine (Josef Polak, Prague).

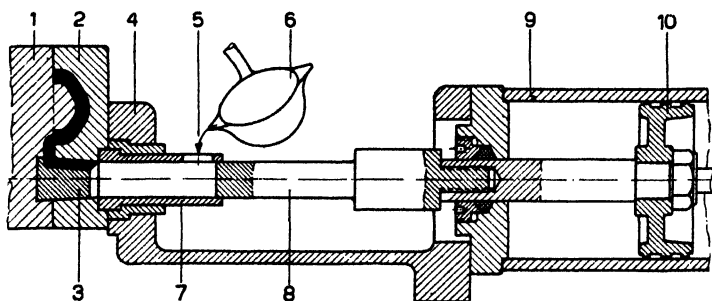
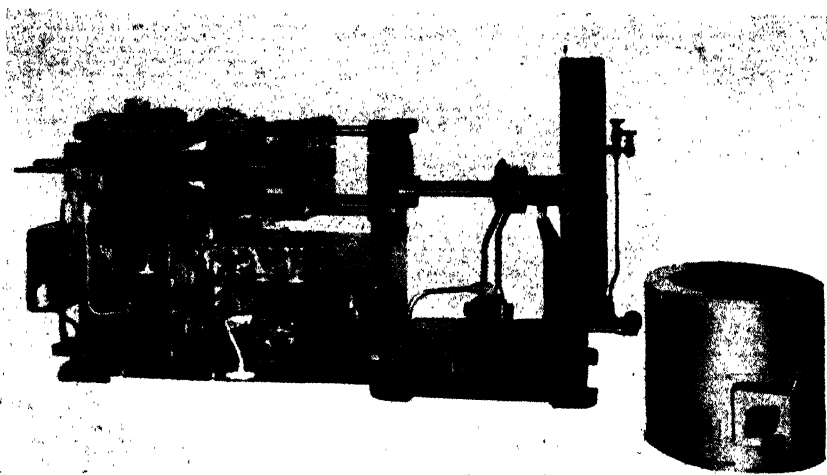


Fig. 173. Pre-casting machine, sectional elevation (Lester-Phoenix Inc., Cleveland, O.).

- |                        |                     |                       |
|------------------------|---------------------|-----------------------|
| 1 Moving half die.     | 5 Pouring slot.     | 8 Wits-alloy plunger. |
| 2 Stationary half die. | 6 Ladle.            | 9 Air cylinder.       |
| 3 Spreader.            | 7 Wits-alloy liner. | 10 Aluminium piston.  |
| 4 Cylinder bracket.    |                     |                       |

following this, the pressure plunger 2 is brought down and forces the metal in its pasty condition into the mould. When the pressure plunger is withdrawn, the ejecting piston 5 pushes the residual solid metal butt out of the chamber. With this type of machine, pressures up to 3000 lbs per square inch can be exerted on the metal. As the receiving chamber is cold, no contamination by iron takes place.

Since the press casting machine is restricted to alloys having a wide solidification range, a type of cold chamber machine known as a pre-casting machine was introduced to deal with pure aluminium and its eutectic alloys with no solidification range. In this type of machine, as shown in Figs. 173 and 174, the molten metal is poured into a pressure chamber at the back, open at the top, which is held at a temperature of 400° to 500°C (752° to 932°F), and is immediately forced into the mould by a plunger. The ejection of the residue takes place through the mould. In another type of pre-casting machine, the pressure chamber is arranged

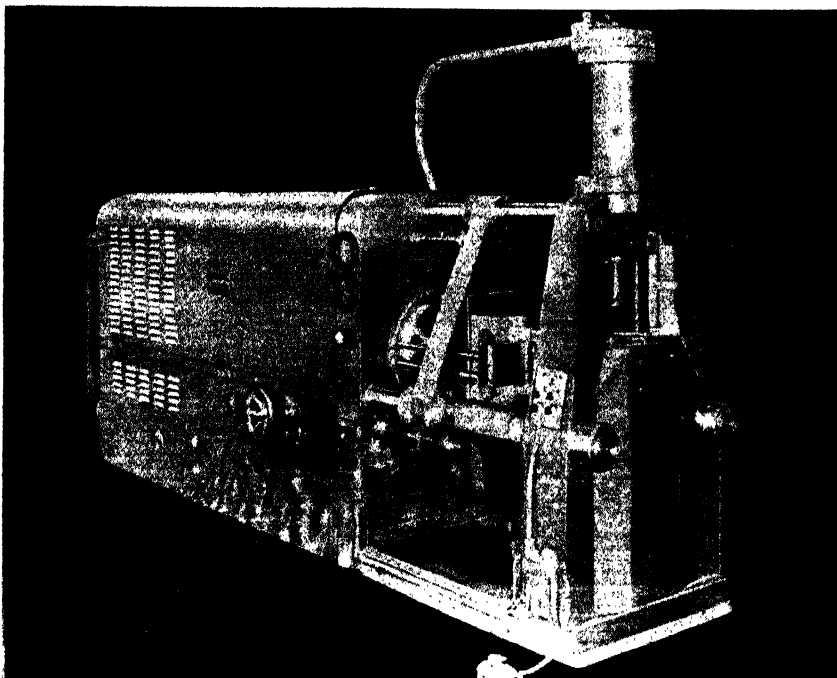


Fig. 174. Pre-casting machine by Hydropress Inc., New York.

vertically as in the press casting machine, and the molten metal is introduced into the pressure chamber in a bag of asbestos cloth. On the down stroke of the plunger, the molten metal is forced from the container into the mould, the bag with excess of metal remaining in the cold pressure chamber. Subsequently the metal residues are separated from the spent asbestos containers by melting.

Whereas in sand and gravity die casting, the formation of shrinkage cavities can be prevented by feeding from the gates and risers, this is not possible with pressure die casting as, owing to the close contact of the metal with the mould in this type of process, a very rapid solidification takes place. Any risers must be closed on the exterior, otherwise metal would spurt from them. Risers are therefore not used and a certain amount of internal porosity is regarded as commercially acceptable in die castings. The lowest porosity is found in pre-castings owing to the incipient solidification of the metal before pressing. In spite of a certain degree of unsoundness, pressure die castings<sup>1</sup> exhibit superior mechanical properties compared with sand castings and gravity castings, owing to their very fine crystal structure, as shown in Fig. 159. The die-casting alloys in general use are listed in Table 26 below.

<sup>1</sup> Or die castings (U.S.A.)

TABLE 26

## PRINCIPAL ALUMINIUM-BASE PRESSURE DIE CASTING ALLOYS

Alloy No.	Composition %				
	Cu	Ni	Mn	Mg	Si
1	1 to 4	—	—	—	3 to 8
2	—	—	0.5	—	6 to 10
3	—	—	0.5	6 to 10	—
4	2	2	—	—	2
5	—	2	—	2.5	4 to 5

## (ii) Die casting dies

The most important component of a pressing die casting machine is the mould or die. Although for gravity die casting the moulds are of cast iron, for pressure die casting they have to be made of forged and heat treated high tensile steel. The alloy content of the steel may be selected according to whether very large numbers of castings are wanted off the die or lesser numbers. For very large numbers off, a die steel with 0.3% C, 2% Cr, 8% W, 0.5% V and 1.5% Co might be used, while for a relatively small number off, the steel might contain 0.4% C, 1.5% Cr, 0.5% Mo and 0.3% V. The dies, as shown in Fig. 175, consist of the fixed front half with the gate or sprue and the conical seat to receive the nozzle of the goose neck, and the moveable back half. The casting is so laid out in the dies that it is pulled out with the moveable back half and comes away

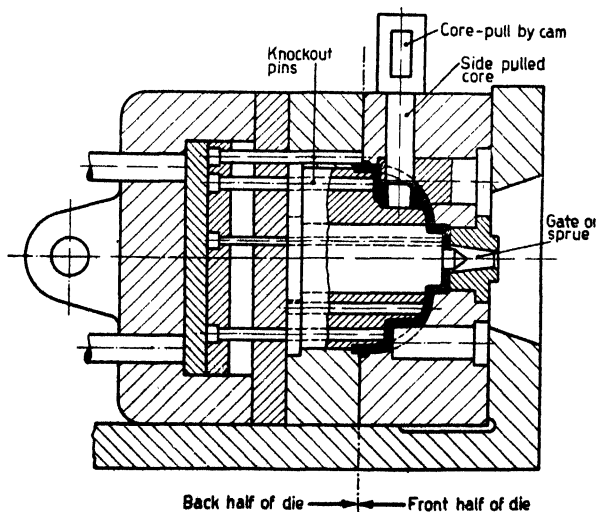


Fig. 175. Pressure die casting dies — in section.

clear from the fixed front half of the die when the die is opened. To assist this, all side-pulling cores must be withdrawn in the fixed front half before the dies are opened. Since the castings completely fill the mould after solidification, owing to the high pressure, it is necessary to provide sufficient knock out pins in the die, which are located on a moveable stripper plate co-acting with the moveable back plate. The high casting pressure ensures

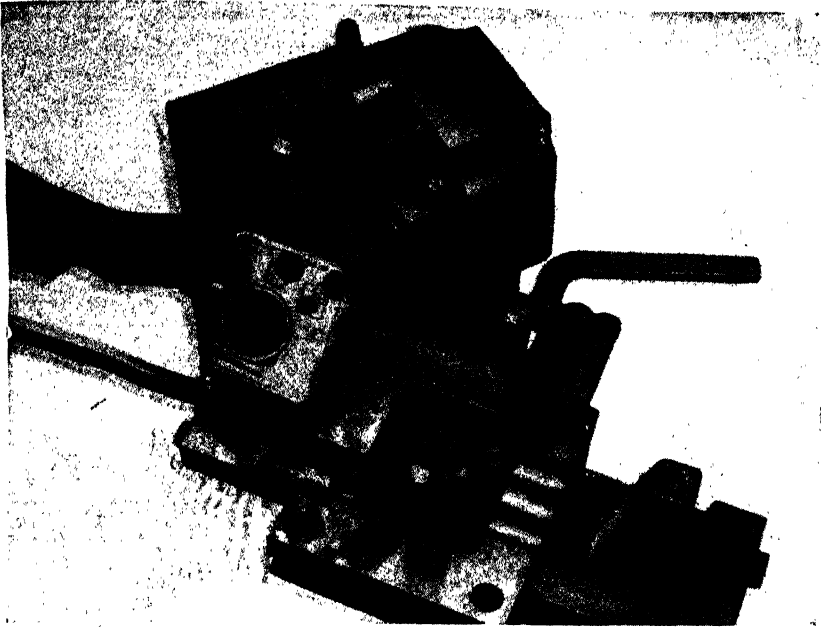


Fig. 176. Pressure die casting die with casting therefrom.

a high degree of dimensional accuracy in pressure die castings, which, depending on the size of the casting is usually within  $\pm 0.2\%$  with a minimum tolerance of  $\pm .004$  in.

The size of pressure die casting that can be produced is dependent on the size of die casting machine available. The biggest machines will make a casting up to 22 pounds in weight and  $24'' \times 16'' \times 12''$ . As high tensile steels are used for the dies, the number of castings that can be made from one die is considerably greater than from the permanent moulds of the gravity die casting process. Generally speaking, after 5000 to 10000 "shots", the die must be reconditioned, while according to the alloy and the quality of the steel, a maximum of 25000 to 50000 castings can be made. On account of the high die costs and their long life, the pressure die casting process is most economical for large quantities off a casting, while for smaller quantities the gravity die casting process is generally to be preferred. With pressure die casting a greater accuracy is obtainable and it is often possible to assemble the castings without machining.

For long runs, the pressure die casting machine is usually fully automatic in operation, so that all motions take place automatically in proper sequence and the operator has simply to keep watch on the working of the machine. With such machines up to 500 shots an hour can be made, whereas with hand operated machines only 25 to 100 shots an hour are usual,



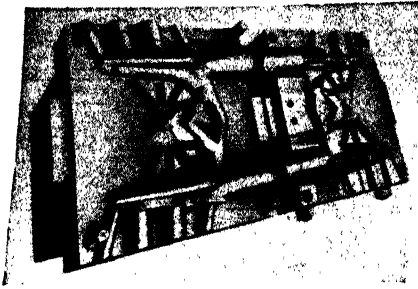
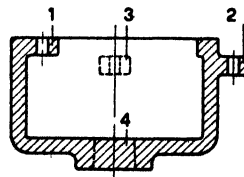


Fig. 177. Pressure die casting dies showing parting faces, gates and casting. (Injecta A.G., Teufenthal, Switzerland).

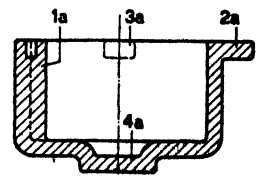
according to the size. In both pressure and gravity die castings, steel or brass inserts can be cast in. Fig. 176 shows the front and rear halves of a pressure die casting mould with the casting from it. In view of the higher accuracy of the pressure die casting mould compared with the gravity mould, the correct making of the die requires special care. The design of such a die casting should therefore be discussed with the die casting

manufacturer before it is finally settled, as it is frequently found that minor modifications will greatly simplify production of the castings.

Fig. 177 shows the two halves of a die casting mould with numerous core slots (the cores being removed) in which the gating arrangement is clearly visible. The sprue or gate is in the middle of the die and 8 runners lead to the casting cavity with uniform distribution. The general rules of light alloy casting design apply equally to die castings: wall thicknesses as uniform and thin as possible and gradual running together of unavoidable changes of sections, avoidance of undercuts and thick bosses, etc. Fig. 178 shows on the left a casting on which the lug 1 requires a sectional internal core, which is not only expensive but wasteful of operating time owing to the under-cut, while the lugs 2 and 3 necessitate a complicated separation of the outer half mould in order to be able to strip the casting from the die. If on the contrary the lugs 2a and 3a as shown on the right, are arranged on the upper edge of the casting, the making of the parting surface of the dies is much simplified, and instead of the internal lug, it is better to have a thick internal rib of full depth which only necessitates the use of a simple one piece core. If there have to be internal lugs therefore, it is advisable to carry them through to the bottom of the casting as at 1a, in spite of the increased use of metal. If a boss around a hole in the casting as at 4 is required, this should be kept sound either by coring the casting as shown dotted in the illustration, or if this is impracticable for any reason, it could then be ascertained whether a dish as at 4a could be used.



Inadvisable



Preferable

Fig. 178. Wrong and right in design of a die casting.



Fig. 179. Keller copying milling machine for die sinking  
(Courtesy of Injecta A.G., Teufenthal).

Fig. 179 shows a milling machine of the copying type on which a die casting mould is being cut from a steel block by following a plaster model.

#### 5. MAGNESIUM CASTINGS

Originally magnesium castings were made only in sand moulds, but recently the casting technique has become so far improved that they can now be produced as gravity and pressure die castings.

##### a. *Casting of magnesium rolling blocks and extrusion billets*

Although aluminium and its alloys are generally melted in large open hearth furnaces, crucible furnaces are still used for magnesium melting, with wrought or cast steel melting pots. It is a common practice to lift the melting pots from the furnace and after fluxing treatment and skimming, to cast the metal direct from them into cast iron moulds. In this process the metal is unprotected by a flux covering, and oxidation must be restricted by directing a stream of sulphur dioxide gas on the metal or by scattering sulphur on its surface. In other respects the casting practice is as for aluminium. Besides being cast in tilting chill moulds, magnesium is also cast into block and billet form by the continuous casting process and in this case also access of air must be prevented by an atmosphere

of protective gas. The earlier assumption that in the latter process water could not be used as the cooling liquid has not been found to be so in actual practice. Even if liquid magnesium does come in contact with water, provided there is a sufficiently great excess, no explosion or ignition takes place.

b. *Sand casting*

For sand casting, alloys with 6%Al, 3%Zn and 0.2%Mn, or 8 to 9.5%Al, 0.4%Zn are used in America, while in Europe alloys with 8 to 9%Al, 0.5 to 1%Zn and 0.3% to 0.5%Mn are those chiefly in use; in these the impurities should run less than 0.005%Ni, 0.07%Cu, 0.02%Fe, 0.02%Ca and 0.1%Si. With the last named alloy it has been found that, contrary to the experience with aluminium, a superheating to 800 to 900°C (1472 to 1652°F) followed by a rapid cooling off to the pouring temperature of 700 to 750°C (1292-1382°F) gives a distinctly finer crystal size in the casting. For this effect, the time at which it is necessary to hold the metal at the superheat temperature is shorter the higher the temperature. At 850°C (1562°F), 30 minutes is necessary, but at 900°C (1652°F), 15 minutes must not be exceeded, otherwise there will again be a tendency to a coarse crystal size. Frequently an addition is made of 0.5% chloride of iron<sup>1</sup> (formerly sold as Elfinal by the I.G. Farben) for grain refinement, in combination with the superheating of the melt. In the most recent practice it has been found that a similar effect can be produced by introducing C<sub>2</sub>H<sub>2</sub>. The effect of chloride of iron is ascribed to the presence of finely divided metallic iron in the melt. This has the disadvantage, however, of reducing appreciably the corrosion resistance. In the case of treatment with C<sub>2</sub>H<sub>2</sub>, this is assumed to form the compound aluminium carbide (Al<sub>4</sub>C<sub>3</sub>) with the aluminium content of the magnesium alloy, which brings about the grain refining effect.

To secure the maximum strength, a heat-treatment is necessary, in which the castings are heated for 5 to 8 hours at 390°C (734°F), followed by 12 hours at 400°C (752°F), and finally 10 hours at 410°C (770°F)<sup>2</sup>. It has also been proposed to extend this treatment for even longer times at each stage of temperature. It is only by the accurate observation of all prescribed conditions that the maximum strength properties of magnesium alloys can be obtained with certainty. Since magnesium begins to become reactive with air above 400°C (752°F), it is necessary to carry out the heat-treatment in a protective atmosphere. An alloy Z5Z has recently been developed by Magnesium Elektron Ltd.<sup>3</sup> with 4.5% zinc

<sup>1</sup> Patented in many countries; Swiss Pats. 232404 and 235476

<sup>2</sup> Swiss patent 186,889 British patent 452,390 U.S. patent 2,087,262.

<sup>3</sup> British patent 567,551.

and about 0.6 % zirconium with which even higher mechanical properties have been obtained.

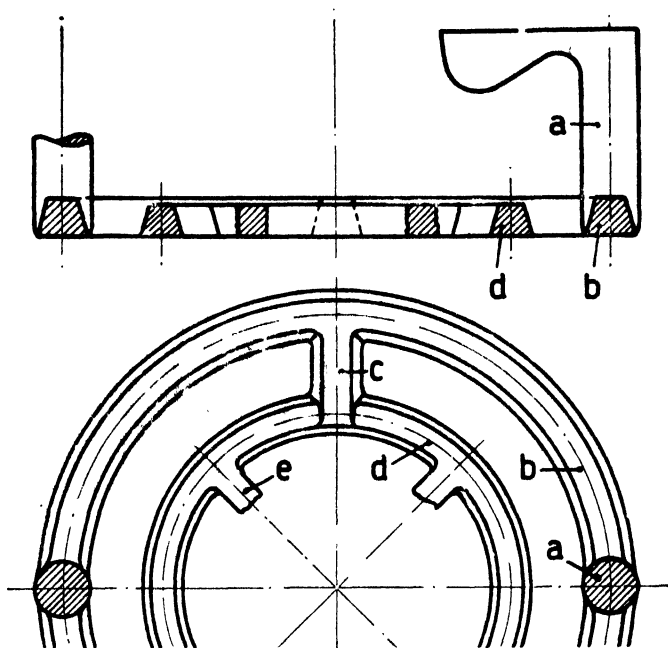


Fig. 180. Gating practice for magnesium casting.

a = 1.5 sq. inch. b and c = 1 sq. inch. d = .7 sq. inch. e = .5 sq. inch.

As a consequence of the very low specific gravity of magnesium, the venting of the moulds and the permeability of the sand is of even greater importance than with aluminium. In the early days, magnesium sand castings were only produced in moulds dried at over  $400^{\circ}\text{C}$  ( $752^{\circ}\text{F}$ ), but it is now possible to cast the metal in greensand moulds with suitable addition agents, which inhibit the water vapour from reacting with the magnesium. Additions generally used are 2% sulphur, 2% boric acid and frequently also 5% diethyleneglycol, and these are mixed with the sand. Smaller additions are made to cores, as these are baked at  $250^{\circ}\text{C}$  ( $482^{\circ}\text{F}$ ). The moulding sand is often composed of a synthetic mixture of silica sand with 5% of bentonite and, beside the above additions, 5% of water is also added to make the sand cohesive. The grain-size of the sand should for the most part be in the range 0.06 to 0.2 mm (.002 to .008 inch) which gives a satisfactory permeability.

With regard to the runners, in moulds for aluminium these are generally arranged flat, while in magnesium moulds as in Fig. 180, they are upright, and it is to be noted that in both cases the mould is always gated at the lowest point so that the metal may fill it in a quiet rising flow. Corresponding



Fig. 181. Magnesium casting bay — A. Stone & Co., Deptford.



Fig. 182. Magnesium sand foundry — A. Stone & Co., Deptford.

to the lower specific gravity of magnesium, the gates must be of greater section or greater height so that a high enough velocity of flow may be attained. Gating practice frequently does not receive the attention it requires. The down-gates and in-gates in both aluminium and magnesium casting should always be so proportioned that they can be kept full, and, without overflowing, the metal can fill the mould from the lowest point in a quiet stream. According to the size of casting, more than one gate may be required, branching into one or more runners as may be necessary. There is a decrease

of resistance to flow in larger sections, and the gates should be dimensioned accordingly.

For the sake of clearness, the casting is not shown in the above-mentioned illustration. From a down-gate or sprue of 1.5 sq. inch section, the metal flows through 2 ring runners of 1 sq. inch section. The end of each runner feeds a ring runner of 0.7 sq. inch section. From this there are in-gates of 0.5 sq. inch section at 4 places into the casting.

Before the metal is cast, the mould is filled with  $\text{SO}_2$  gas. This and the sulphur added to the sand give rise in casting to objectionable though harmless sulphur dioxide fumes. To avoid discomfort to the foundrymen

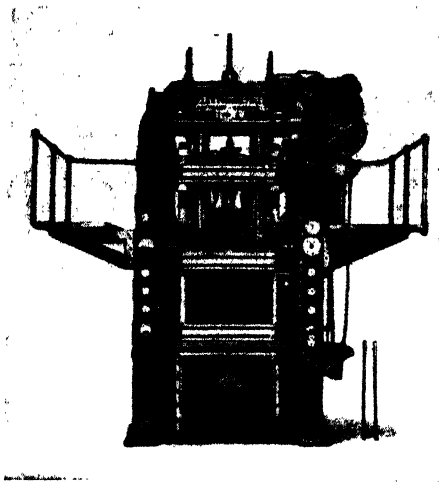


Fig. 183. Fully automatic pressure die casting machine for magnesium (Mahle Komm. Ges. Stuttgart-Bad Cannstatt.).

from this cause, in modern foundries, the moulds are transferred for pouring to a well-ventilated pouring shop adjoining the moulding shop. Fig. 181 shows a shop of this kind in which two long tunnels can be seen in the background into which the moulds are pushed after casting to cool down and from which the sulphurous air is extracted. At the end of the tunnel the moulds are knocked out and the boxes are sent back to the moulding shop, while the sand goes to the conditioning plant. Fig. 182 shows the adjoining moulding shop for heavy castings; in the light moulding shop, moulding machines are installed.

### c. Gravity and pressure die castings

With intelligent application of the principles given for sand castings, magnesium can be gravity die cast in permanent moulds in a similar manner to aluminium.

For magnesium pressure die casting, special machines are used, in which the pressure chamber and the enclosed melting vessel are held under a protective atmosphere. Compressed nitrogen is used as the working fluid for the pneumatic pressure instead of compressed air. Fig. 183 illustrates a fully automatic magnesium die casting machine of this type, in which the melting vessel is accommodated in the lower portion of the machine. For die construction and die design, the principles laid down for aluminium hold good for magnesium.

## CHAPTER VII : ROLLING

### 1. PLASTIC DEFORMATION. GENERAL CONSIDERATIONS

Next to casting comes plastic deformation by the rolling, extrusion, forging, impact extrusion, drawing and spinning processes. Plastic deformation is usually described as mechanical working, and the particular working process is given. The working of the cast block or billet brings about a refinement of the grain-size and an improvement in the structure of the metal, often falsely described as densening. Important results of plastic deformation are an increase in elongation and toughness as well as a general increase in strength properties compared with the same alloy in the as-cast condition. Above all, wherever there is the demand for the highest uniformity and soundness of the material, the use of plastic deformation is the best way of achieving this.

By virtue of the greater number of slip planes in the face-centred cube space-lattice of aluminium, this metal is capable of being more readily worked in any direction than magnesium and high magnesium alloys, which owing to the hexagonal lattice, are only deformable parallel to the basal plane, see Fig. 184. This peculiarity of magnesium is apparent even in the aluminium alloys with 5% and 10% of magnesium. In cold working, the material undergoes a progressive work-hardening which limits the degree of cold work that may be applied, but hot working is carried out at a temperature above that of recrystallisation and thus no work-hardening

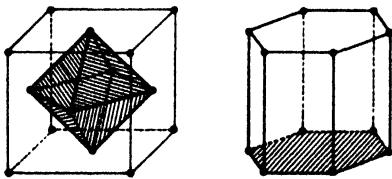


Fig. 184. Slip planes in aluminium and magnesium single crystals.

Slip planes on octohedral planes in Al.  
Slip planes on basal planes in Mg.

comes about, so that the percentage reduction in hot rolling is practically unlimited. By annealing, cold worked material is restored to its maximum softness and workability. Table 27 gives the hot rolling temperatures of different alloys and the limiting degree of safe cold reduction, as well as their annealing and heat-treatment temperatures.

### 2. POWER CONSUMPTION IN ROLLING

The power consumed in the deformation of metals is a matter of fundamental importance. Accurate investigations into the pressure required



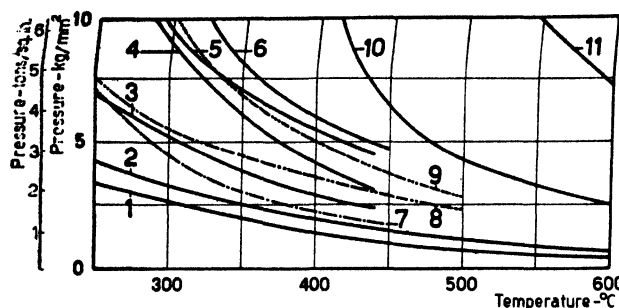


Fig. 185. Compression pressure in pressing cylinders of different alloys.

- |                                 |                        |
|---------------------------------|------------------------|
| 1 Pure al., 99.99%.             | 6 Y Alloy.             |
| 2 Pure al., 99.5%.              | 7 Pure magnesium.      |
| 3 Anticorodal (Al-Si-Mg).       | 8 Aviomag KM (Mg-2Mn). |
| 4 Avional D (Duralumin).        | 9 Aviomag K6 (Mg-6Al). |
| 5 Avional SK (Super Duralumin). | 10 Brass.              |
|                                 | 11 Copper.             |

and energy absorbed in the compression of various metals have provided the data for a study of this. Fig. 185 shows the compressive pressure in upsetting cylindrical specimens of 20 mm in diameter and 20 mm in height at different temperatures under a hydraulic press, and Table 28 gives a comparison of the pressure required and energy absorbed by different materials at the optimum working temperature in pressing, and upsetting under a drop hammer respectively, the quantity of energy absorbed under the drop hammer by the pure aluminium specimen being taken as unity. The tests show that there is considerable difference between pure aluminium and the Al-Mg alloys, which are the hardest to deform, and that the hardest aluminium alloys require more pressure for their deformation than mild steel.

TABLE 27

TEMPERATURES FOR THERMAL PROCESSES

Material	Hot working temperature °C**		Maximum permissible cold reduction %		Annealing temperature °C**	Heat-treatment temperature °C**	
	Highest (start)	Lowest (finish)	Total	Per pass		Solution	Precipitation
Pure aluminium . . .	450—500 (842—932)	300 (572)	70—95	50	360—400 (680—752)*	—	—
Anticorodal . . . . .	450—500	400	60—85	25	340—370 (644—678)	530—550 (986—1022)	155—160b (311—320)
(Al-Si-Mg) . . . . .	(842—932)	(752)	—	—	—	520—540 (968—1004)	155—160b (311—320)
Aluminium . . . . .	—	—	—	—	—	500—520 (932—968)	155—160 (311—320)
(Cast-2.5%Si) . . . . .	—	—	—	—	—	505—515 (941—959)	15—25 (59—77)
Aldrey . . . . .	480—500	450	90—95	25	300—320 (572—608)*	—	—
(Al-Mg-Si) . . . . .	(896—932)	(842)	—	—	—	—	—
Avional D . . . . .	400—450	360	60—85	20	340—370* (644—698)	—	—
(Duralumin) . . . . .	(752—842)	(680)	—	—	—	—	—
Aluman . . . . .	450—520	450	60—85	25	450—500 (842—932)	—	—
(Al-Mn) . . . . .	(842—968)	(842)	—	—	—	—	—
Peraluman 3 . . . . .	400—450	400	30—50	15	360—400 (680—752)	—	—
(Al-3Mg) . . . . .	(752—842)	(752)	—	—	—	—	—
Peraluman 5 . . . . .	330—360	330	30—50	15	300—310 (572—590)	—	—
(Al-5Mg) . . . . .	(626—680)	(626)	—	—	—	—	—
Peraluman 7 . . . . .	330—360	330	30—50	15	290—300 (554—572)	—	—
(Al-7Mg) . . . . .	(626—680)	(626)	—	—	—	—	—
Silumin Gamma . . . . .	—	—	—	—	—	500—510 (932—950)	145—155 (293—311)
(Silafont 2) (Al-Si) . . . . .	—	—	—	—	—	510—520 (950—968)	170—175 (338—347)
Y alloy . . . . .	440—480	400	30—75	20	400—420 (752—785)	—	—
(Al-Cu-Ni) . . . . .	(824—896)	(752)	—	—	—	—	—

\* higher for larger sections

b = precipitation temperature for hard quality

\*\* °F in brackets

TABLE 28  
ENERGY CONSUMPTION IN FORGING

Alloy Type (VSM 18046 E-Al) (VSM 10890 E-Mg)	Alloy Tested	Mean forging temperature		Pressure for 50% up- set of the specimen			Relative degree of upset under drop hammer	
		°C	(°F)	kg/mm <sup>2</sup>	Tons/sq. in.	1000 lbs. /sq. in.	%	1
Al (VSM10840/41)	99.3% pure al. .	525	(977)	1.0	.6	1.3	33	1
Al-Si-Mg	Anticorodal . . .	450	(842)	2.8	1.8	4.0	20	0.6
Al-Cu	25S (USA) . . .	450	(842)	3.5	2.2	4.9	—	—
Al-Cu-Mg	Avional (Dural- umin) . . . . .	400	(752)	4.4	2.8	6.3	10	0.3
Al-Cu-Mg	Superalunal. . .	400	(752)	5.4	3.4	7.6	8	0.2
Al-2Mg	Peraluman 2 . . .	410	(770)	4.8	3.0	6.7	15	0.4
Al-7Mg	Peraluman 7 . . .	350	(662)	9.8	6.2	13.9	8	0.2
Mg	Pure magnesium .	460	(860)	1.8	1.1	2.5	—	—
Mg-6Al	Aviomag K6 . . .	370	(698)	6.3	4.0	9.0	11	0.3
Mg-2Mn	Aviomag KM . . .	460	(860)	3.0	1.9	4.3	22	0.6
	Brass (58) . . . .	700	(1292)	2.4	1.5	3.4	17	0.55
	Mild steel . . . .	1000	(1832)	4.5	2.9	6.5	10	0.3

<sup>1</sup> In this column is given the magnitude of the compression for the various materials compared with pure aluminium = 1.

Top row 5 strikes: Bottom row 10 strikes

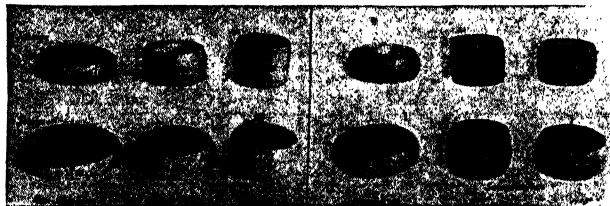


Fig. 186. Degree of deformation of cylinders 80 mm diameter by 80 mm high under the drop hammer.

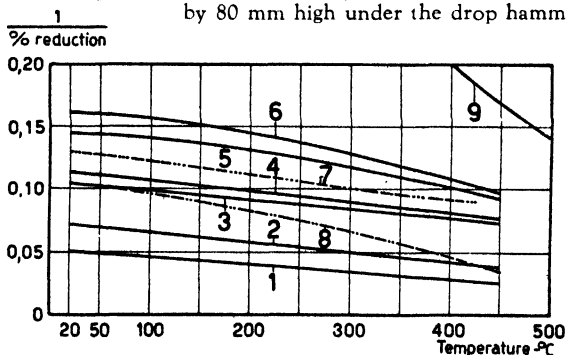


Fig. 187. Reciprocal percentage reductions under the drop hammer for comparison with the compression pressures in Fig. 185.

- 1 Pure aluminium, 99.5.
- 2 Anticorodal (Al-Si-Mg).
- 3 Avional D (Duralumin) (Al-Cu-Mg).
- 4 Peraluman 3 (Al-3Mg).
- 5 Peraluman 5 (Al-5Mg).
- 6 Peraluman 7 (Al-7Mg).
- 7 Aviomag K6 (Mg-6Al).
- 8 Aviomag KM (Mg-2Mn)
- 9 Brass.

Fig. 186 shows the result of upsetting tests on cylinders of 80 mm diameter by 80 mm height under a drop hammer of 270 kg weight with height of fall  $1\frac{1}{2}$  metres with 5 and 10 successive strikes at the usual forging temperature. To give a comparison of the deformation under the drop hammer with the compression pressure under the press, Fig. 187 shows a comparison of the reciprocal value of the amount of upset (or reduction in height of the specimen), at

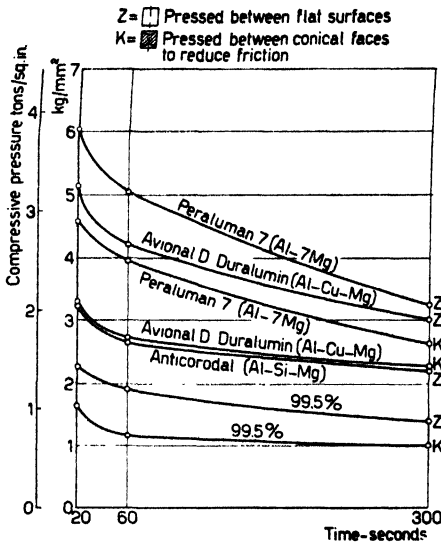


Fig. 188. Effect of speed of deformation on pressure of deformation.

different temperatures for the different alloys. The effect of the speed of deformation on the compressive pressure is shown in Fig. 188 from which it can be seen that an increase in the speed leads to an appreciable increase in the pressure and consumption of energy. In this test, cylinders 20 mm in diameter by 20 mm in height were upset under the hydraulic press by 10 mm, that is a 50% reduction.

### 3. ROLLING MILLS

The rolling mill was introduced in England in 1783 for heavy metals, plastic deformation having previously been only carried out by forging.

At first 2-high mills were used (Fig. 189) in which either the rotation of

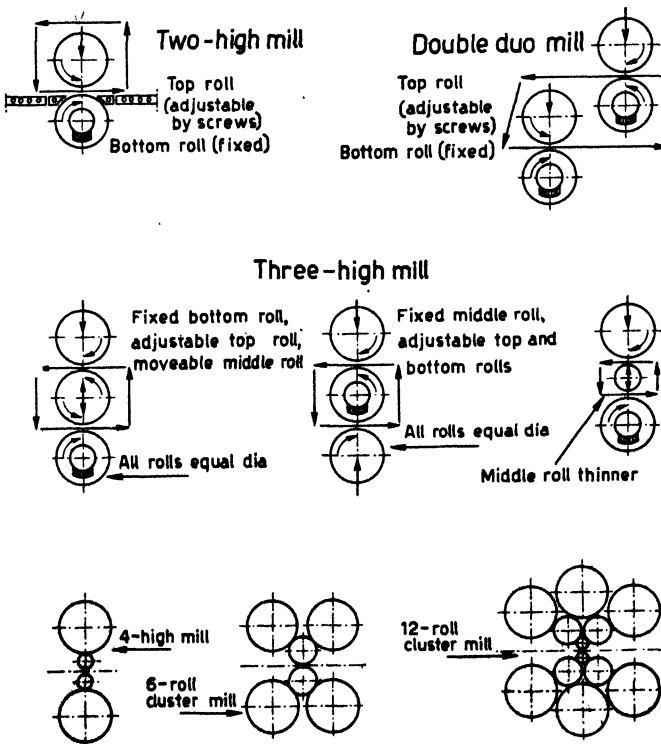


Fig. 189. Types of rolling mill.

the rolls was reversed after each pass of the piece through the rolls, or when non-reversing mills were used, the piece was passed back over the rolls. The great absorption of energy by the rolling mill during the rolling pass usually made the use of flywheels necessary to boost the torque, and with flywheels a reversal of the direction of rotation had to be obtained with a reversing clutch. As these arrangements were not altogether satisfactory, there was a transition to the continuous running double-*duo* or double two-high mill and finally to the three-high mill, in which the piece is rolled in one direction between the lower and middle rolls and in the reverse direction between the middle and upper rolls. In the three-high mill, in one arrangement the lower roll is fixed, the upper roll adjusted by the screws, and the middle roll raised or lowered alternately against the upper and lower rolls, or, in a different arrangement, the middle roll is fixed and the upper and lower rolls are each adjusted independently by screws to the desired pass opening. The second arrangement is in very little use for aluminium. If the middle roll is in contact during the pass with the upper or lower roll, it is supported by this against the rolling pressure and is therefore deflected to a smaller extent. The diameter of the rolls is proportioned to the duty they have to perform, and depends on the length of the roll barrel, the hardness of the stock and the draft or reduction of the pass. The bigger the diameter of the rolls, the greater the rolling pressure for a given material and draft. For this reason, a thinner middle roll (as originally introduced in the LAUTH mill) is frequently used in three-high mills. The use of a thin middle roll is not satisfactory for the hot rolling of light metal blocks, owing to the curling imparted to the stock (Fig. 190). In order to make satisfactory use of thin rolls they are incorporated in 4-high, 6-roll and even 12-roll cluster mills. For the hot rolling of aluminium alloys, 4-high mills are in use, while 6-roll cluster mills are sometimes used for the cold rolling of hard strip.

Fig. 191 shows the arrangement of a 3-high mill. In modern plants, the fly wheels are mounted on the high speed spindle. The expensive driving gears must be protected against overloads from the flywheels when the mill is stalled, by suitable safety couplings. Likewise the roll housings and the rolls themselves are protected against breakage under

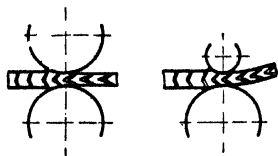


Fig. 190. Effect of equal and unequal roll diameters on deformation.

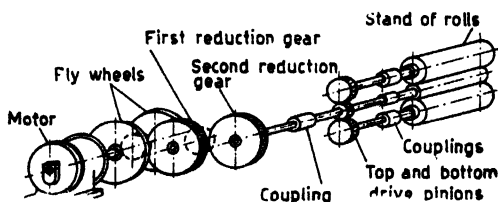


Fig. 191. Roll driving gears.

overload, by suitable breaker blocks. In general the spindle couplings serve as safety breaking elements, and breaker blocks fitted between the roll bearings and the roll screws form additional safeguards.

#### a. Hot rolling

The rolling process generally comprises the initial hot rolling of the cast block, followed thereafter by cold rolling. To commence with, the cast structure of the rolling block must be converted to a lamelliform rolled structure. This is more readily achieved the finer the crystal grain of the rolling block and the fewer the alloy constituents occurring at the grain boundaries. The segregated components can be dissolved by annealing or homogenising for several hours. Alloys of the Al-Mg and the Al-Cu-Mg type that are difficult to roll are in some cases first extruded from cast billets. For reasons of lower cost of production, the heaviest possible rolling blocks are processed in hot rolling, sometimes up to 1 ton weight in the light alloys. Cold rolling is done either by strip rolling a coil of the same weight, which is drum coiled when it is reduced to a suitable thickness, or by sheet rolling small blanks sheared from the hot rolled or rough cold rolled plate. The thickness or gauge of plate to which hot rolling is carried, is determined according to the finished gauge of the cold rolled sheet, a reduction of 60 to 80% in cold rolling always being required to give optimum strength. The reduction in rolling is expressed as a percentage reduction according to the formula  $\frac{h_1 - h_2}{h_1} \cdot 100$  where  $h_1$  is the thickness

before, and  $h_2$  the thickness after each pass. Owing to loss of heat, the hot rolling process is in the older mills usually stopped at a thickness of 3/16 to 5/16 inch even for thin sheet manufacture. In modern continuous hot mills, however, the stock is hot rolled to 0.1 inch in one heating. In the hot rolling process, part of the heat of the metal being rolled is transferred to the rolls, but these should not be allowed to rise higher in temperature than 200° to 300°C (392° to 572°F), otherwise the metal will stick to the rolls. Continuous cooling of the rolls by a soluble oil emulsion or by soft water is therefore necessary. It is also common practice for the rolls to be bored up the axis and to be provided with bore-cooling.

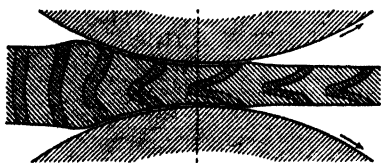


Fig. 192. Deformation of stock in rolling (Hollenberg).

As shown in Fig. 192, slip takes place between the stock and the rolls in rolling due to the extension of the stock in the pass. To reduce the amount of energy lost in friction, the roll barrels are liberally lubricated with rolling oil. As the hot rolled sheets or coils in

many instances requires annealing, a non-carbonising oil which evaporates without residue is used.

Although rolling is a very complex dynamic process, simple methods of calculation for the resistance to deformation, the rolling load and the torque have been worked out<sup>1</sup>. Using as a basis the tests on compression pressure under a press (see Table 28), the specific surface pressure  $K_s$  or resistance to deformation can be found thus:  $K_s = \frac{P}{A}$  where  $P$  is the force exerted by the press and  $A$  the surface under pressure. With this SIEBEL finds the total rolling load from the following formula:

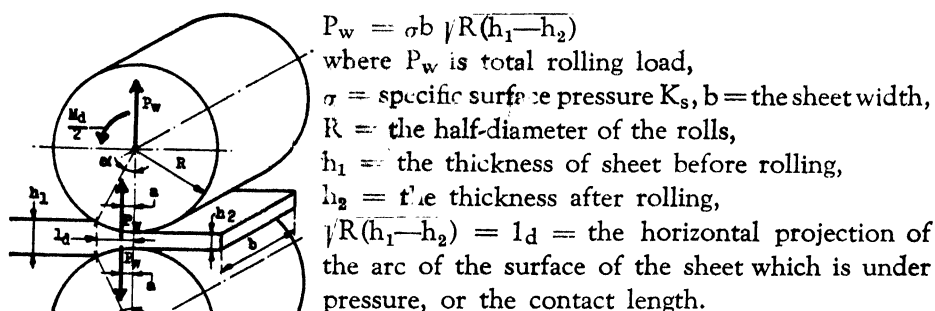


Fig. 193. Force diagram for plate rolling (assumed in equilibrium).

Fig. 193 shows the forces that exist in the rolling process. The total torque  $T$  (or  $M_d$ ) in the roll neck is given approximately by the formula  $T = 2a.P_w$ . From the formula for the total rolling load, it is seen that the effect of the roll half-diameter  $R$  is that the projected contact length  $l_d$  and the total rolling load diminish when the diameter decreases. The reduction in the frictional loss, which is proportional to the rolling load, implies that beside a reduction in the load on rolls and roll housings, the power required will also be less.

The speed of the rolls must be so selected that the plastic deformation does not take place at too great a velocity, otherwise there will be an increase in power consumption.

Experience has shown that for the softer light alloys, rolling speeds up to 900 feet per minute are permissible, while for the hard alloys, especially in the stage of the breaking down of the cast structure, the rolling speed is reduced to 100

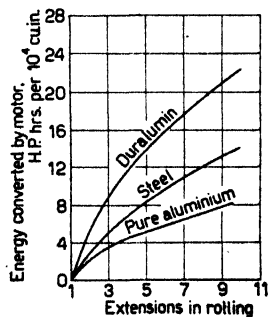


Fig. 194. Energy consumption in rolling (Streeter).

<sup>1</sup> SIEBEL, *Stahl und Eisen*, Vol. 41 (1923) p. 1295. L. SIEBEL, *Die Formgebung im bildsamen Zustande*, Verlag Stahleisen, Düsseldorf 1932. W. KRAMER, *Aluminium*, Vol. 24 (1942) 390. O. EMICKE, *V.D.I. Zeitschrift*, Vol. 87 (1945) 435.

feet per min. Fig. 194 gives a comparison of the power consumption with Duralumin, pure aluminium and steel, in which the considerably greater power required by the Al-Cu-Mg alloy compared with steel is evident. Fig. 195 shows one of the largest 4-high mills for aluminium alloys, with thinner work rolls.



Fig. 195. Heavy Mesta 4-high hot rolling mill for light alloys (Alcoa).

Hot rolling must be carried out as rapidly as possible, so that the plate is finished at the correct hot rolling temperature, and on the other hand at the commencement of hot rolling a low rate of deformation is called for to avoid cracking of the metal when breaking down the cast structure. To attain these objects, it is a common practice to employ 2 hot mills, one following the other as in Fig. 196. The first is a low speed reversing mill with a speed of 130 feet per minute, capable of reducing an 8 inch

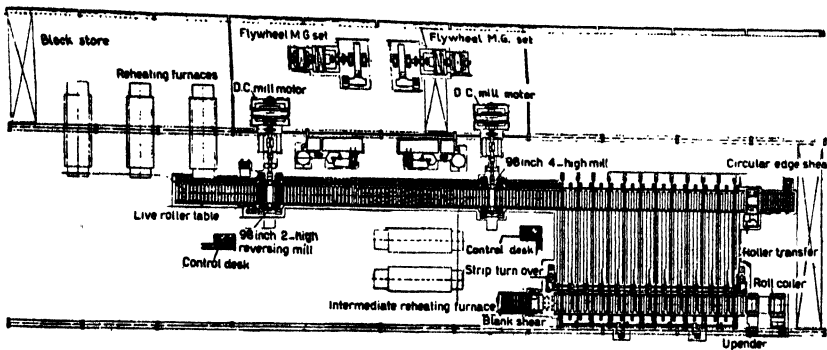


Fig. 196. Layout of hot mill with 2 stands (E. Ullmann).

thick block of Al-Cu-Mg alloy to 4 inches thick in 50 seconds using ten passes. After this the slab goes to a 3 high mill with a constant speed of 450 feet per minute in which it is reduced hot to a final thickness of .280 inch in 150 seconds, using 20 passes. Fig. 197 shows the speed of rolling with different types of mill. In one of the latest modern high capacity mills<sup>1</sup> the reversing 4-high mill is driven by a 5000 horsepower D.C. motor giving a rolling speed of 130 to 450 feet per minute. The first rough rolling to slab is followed by a further intermediate rolling on another similar single 4-high mill. Sometimes there is a second re-heating between these two rolling operations. From this the plate goes to a 5-stand tandem hot mill on which it is reduced in one run to .100 to .120 inch thick. Thus in this latest type of mill, there is in all a total of 7 stands of rolls. As shown

<sup>1</sup> The rolling of aluminium sheets in the Alcoa plant at Trentwood, *Metal Industry*, Vol. 64 (1944) No. 13, p. 194.

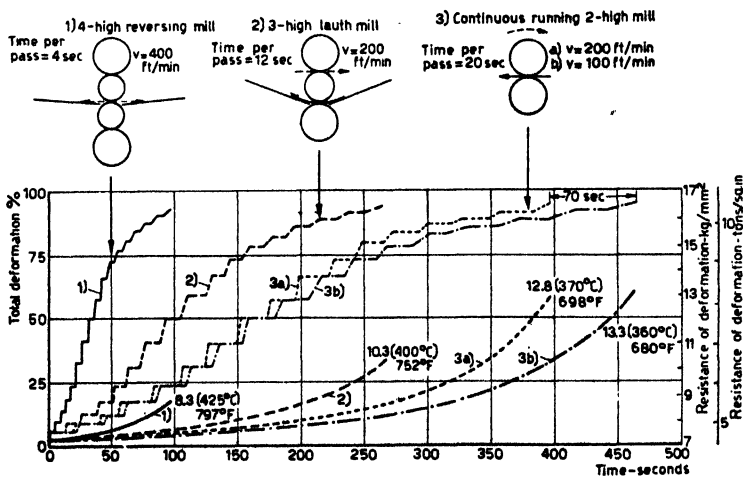


Fig. 197. Rolling times and pressures in hot rolling Duralumin on mills of different types and speeds (E. Emicke) "Time per pass" signifies interval between passes.



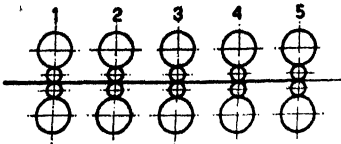


Fig. 198. Grading of speeds in a multi-stand continuous mill.

Roll speed ft./min.	364	458	574	610	900	
Stock thickness inch	.360	.296	.236	.188	.152	.120
% reduction	22	20	20	19	21	

in Fig. 198, in a tandem continuous train of rolls, the roll speed in each stand must be accurately matched with the others, varying proportionally to the reduced thickness of the stock. Fig. 199 shows the run-out table of such a modern American continuous mill and gives an idea of the dimensions and powering. Fig. 200 shows a so-called structural plate mill of 11 feet barrel width with a thin middle roll, as used for the production of very large plates up to 50 feet long and  $\frac{1}{8}$ th inch thick.

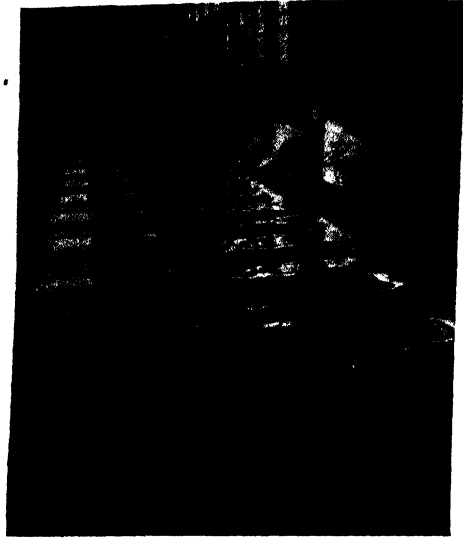


Fig. 199. Run-out table of a United Engineering and Foundry Co. continuous mill (Alcoa, Trentwood).

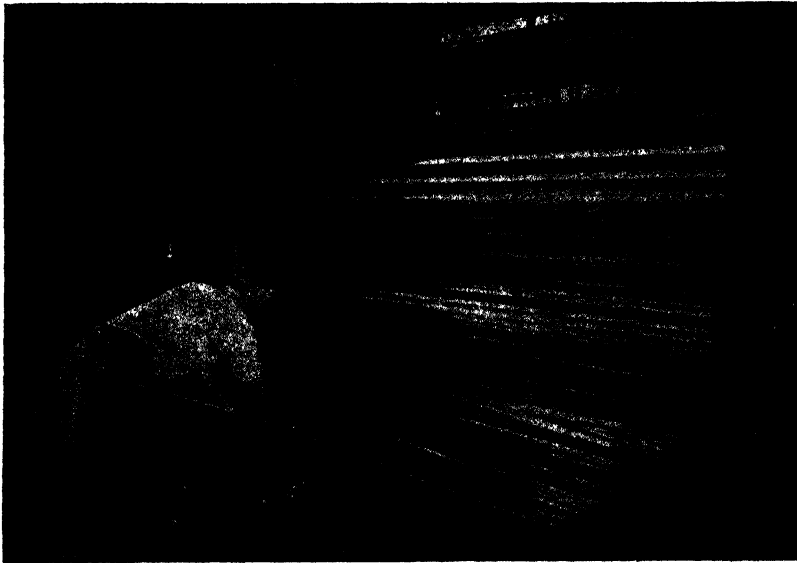


Fig. 200. Lauth-type 3-high plate mill (A.I.A.G., Chippis).



Fig. 201. 3-high friction mill (Achenbach).

### b. Cold rolling

Though the upper and lower rolls in heavy 3-high plate mills are rigidly coupled to the drive, the middle roll is in many cases driven through a slipping clutch. In cold rolling mills, a slipping clutch drive is frequently fitted to the top roll also, while in thin sheet mills, it is common practice for only the bottom roll to be driven, the middle and upper rolls being merely friction driven via the bottom roll. Fig. 201 shows a 3-high friction mill. Slipping of the rolls one each other is unavoidable in the friction mills, and

causes the roll surfaces to develop defects which are impressed on the sheets. When the sheet enters the rolls, the upper roll is suddenly lifted and takes up against the screws, this method of working thus being limited to a maximum sheet thickness of .160 inch, otherwise the impact would be too great. When high surface quality in the product is the chief requirement, 2-high mills with top roll drive are used, which though giving a smaller output, have the advantages of a better roll surface.

To give an absolutely uniform quality of sheet in all directions, it is of advantage to change the direction of rolling between the hot and cold rolling operations. Fig. 202 gives a comprehensive picture of the scrap which is formed in the rolling process. Starting with the block, according to the type of alloy and the quality required in the sheet, the following scrappages must be allowed for:

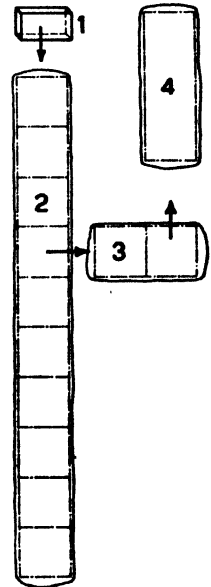


Fig. 202. Changes in rolling direction in sheet rolling, and formation of scrap.

- 1 = 0—4% scrap.
- 2 = 5—10% "
- 3 = 4—8% "
- 4 = 6—10% "

Scalping of the cast block	0—4%
Shearing the hot rolled blanks	5—10%
Overhauling the surface of hot rolled blanks	0—2%
Intermediate shearing	4—8%
Overhauling the surface of sheets in cold rolling	1—2%
Final shearing	6—10%
Stretching machine scrap	0—3%
Rejections on inspection due to surface defects or low physical properties	0—10%
Test pieces	0—2%
Total	<u>16—50%</u>

The higher scrappages are for the difficult high-strength alloys, while the lower are usually only found in the case of pure aluminium sheets. With strong alloy sheets the cold rolling process is usually carried out in two stages, intermediate rolling and finishing, there being an anneal before each stage. After finish rolling, heat-treatment follows, comprising solution heat-treatment and quenching, while to finish with there is a planishing process, carried out on rolls giving a low reduction of only 1 to 2%, which eliminates a part of the distortion in the sheet which arises in quenching. Fig. 203 is a schematic illustration of the individual production processes and the mills required for each. The increased surface area of the sheet

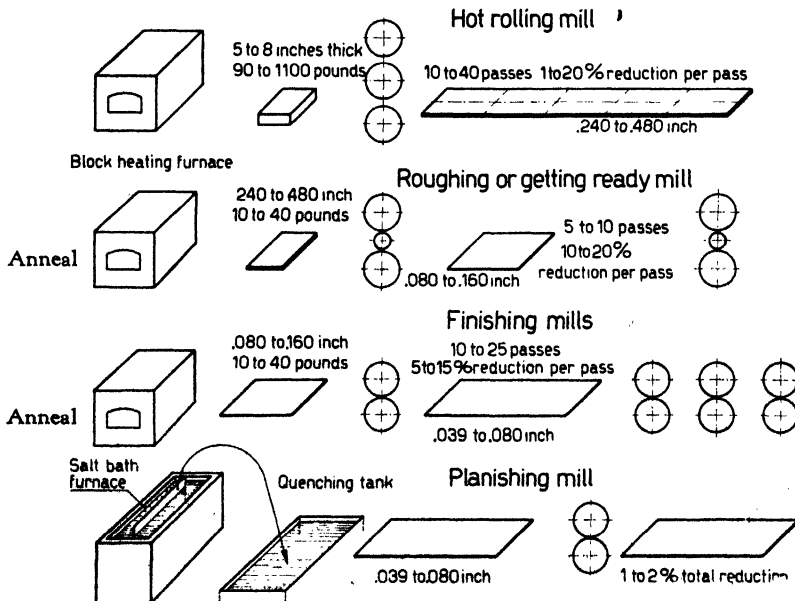


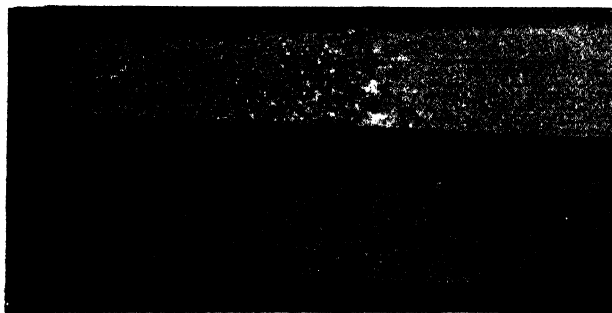
Fig. 203. Sheet rolling processes.



Fig. 204. Effect of percentage extension in flattening on grain-growth.

requires twice as many mills for the finishing rolling process as for a similar percentage reduction in intermediate rolling.

If light alloys are only cold rolled for a small percentage reduction and then annealed, grain growth takes place<sup>1</sup> which gives rise to an undesirable surface quality after further deformation. For aircraft construction particularly, the Al-Cu-Mg alloy should not be affected by exaggerated grain growth. With a certain manganese content, there is obtained a moderately fine-grained structure after a cold rolling reduction of about 20% before the last intermediate anneal by slow heating to 380°C, and after a final low reduction and heat-treatment there is not, under such conditions, a tendency to a coarse grain-size. For the control of this property, the wedge



• Fig. 205. Wedge tensile test.

tensile test shown in Fig. 205 is carried out. In this, wedge shaped strips of sheet are pulled on a tensile testing machine, then heat-treated and quenched. Owing to their wedge shape, the strips have an increasing elongation

<sup>1</sup> Fig. 204.

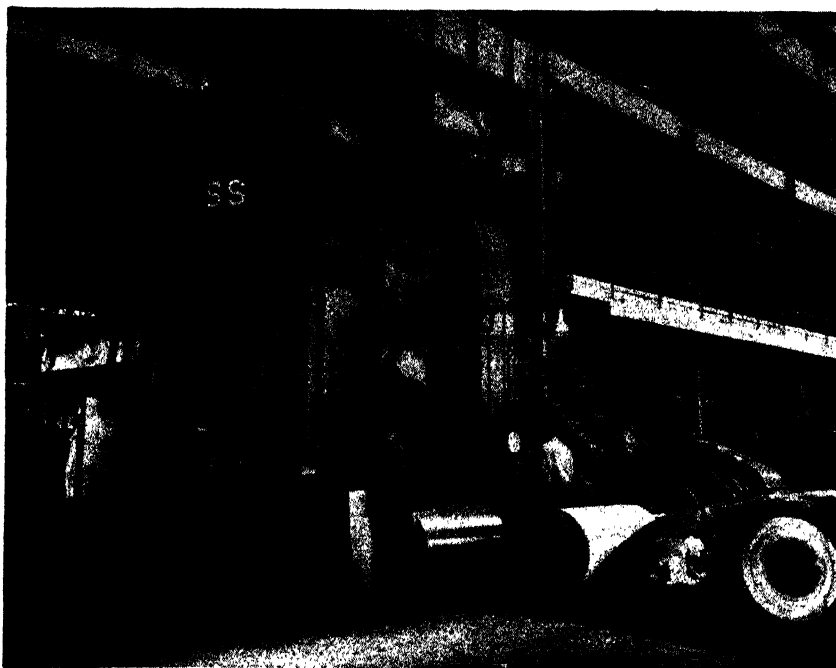


Fig. 206. Heavy Bliss 4-high strip mill (Alcoa).

up to about 20% at the fracture, and thus there is a region which will have the greatest tendency to grain growth. As shown in the illustration, there is, in the case of Avional (Duralumin), a scarcely noticeable grain growth with correct treatment. Such material is designated as deep-drawing quality.

#### *c. Strip and foil rolling*

Hot rolled plate or blank of the full weight of the block is rolled down on strip rolls, as shown in Fig. 206. From a thickness of about .080 inch downwards, the strip is wound on drums. This differs from sheet rolling in which the sheets are always untensioned in the mill, whereas in strip rolling, the strip runs through the rolls under tension. During the rolling operation, owing to uneven heating or other inequalities, it is necessary to be able to adjust one roll screw only in order to avoid the strip running off to one side. To allow for this, very powerfully geared roll screws are provided. Further reduction ceases to be possible at .012 inch to .002 inch, according to the hardness of the strip, owing to the elastic flattening of the rolls under the high rolling pressure. In most cases, assistance in further reduction is obtained by pack rolling the sheets or doubling the strip. It is found that with a combination of tension and pressure in the

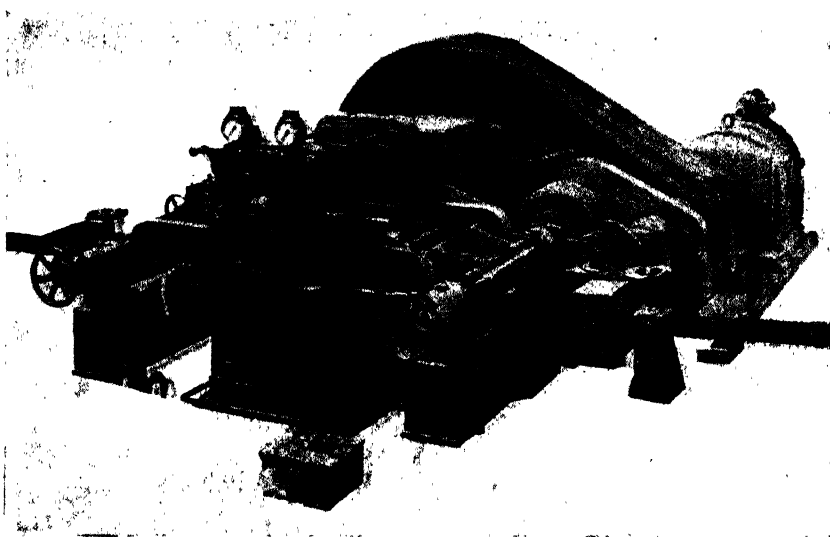


Fig. 207. Foil mill (W. H. A. Robertson & Co. Ltd. Bedford, England).

so-called foil mills (Fig. 207) further reduction of thickness can be carried out to a few thousandths of a millimetre. The strip is brought under tension by tending to vary the drum speed compared with the rolls, and with the pressure effect of the rolls combined with the tension effect of the drums, a greater rate of reduction is obtained. At the ingoing side, the unwinding drum is braked and the strip on this side is also tensioned in this way with benefit to the reduction.

As in hot rolling, so also are continuous cold strip mills now in use (see Fig. 208 a and b). To counteract the heating of the stock during the cold rolling, it is cooled by an air blast between the stands. In cold rolling also, the roll speeds of the various individual stands must be accurately set in relation to each other, and graded driving gears and individual motor speed control are required for this. Sometimes the roll speeds are automatically adjusted according to the tension in the strip.

#### d. *Cambering of rolls*

Even the stiffest rolls are deflected under the pressure of rolling, and thus deflection must be counteracted by the shape of the roll as in Fig. 209. This shape, which is thicker in the middle, is known as the camber, and, depending on the dimensions of the roll and the pressure used in rolling, the camber may be from .02 to .5 mm difference in diameter. A certain camber implies a certain rolling pressure for a given alloy. If the

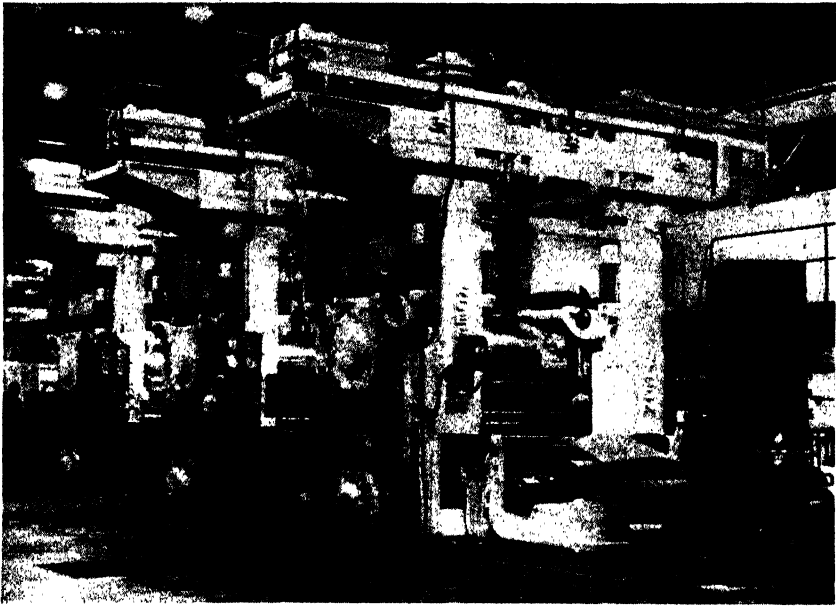


Fig. 208a.

4-high 3-stand tandem continuous cold strip mill (W. H. A. Robertson & Co. Ltd.).

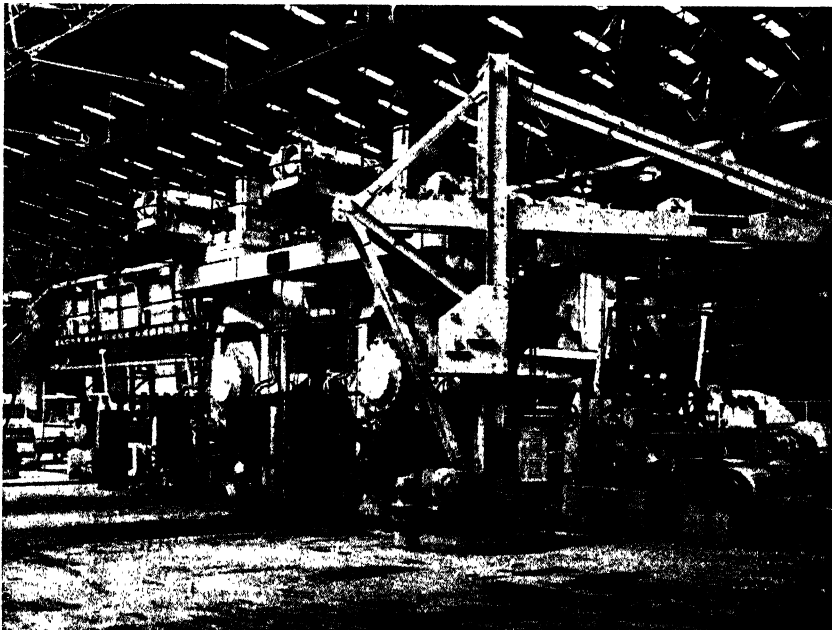


Fig. 208b. 84'' 2-stand tandem 4-high continuous cold strip mill for light metals, at the Falkirk works of the British Aluminium Co. Ltd., designed and built by W. H. A. Robertson & Co. Ltd., Bedford, England.

camber is too great or the pressure too light, the sheet is rolled thin in the centre and has a wavy middle. On the other hand if the camber is too small or the pressure too great, the sheet is rolled thin at the edges and these are then wavy. The roll operator thus has to arrange to roll perfectly

flat sheets through the correct setting of the pinch. Since the rolls expand when hot and the necks of the rolls being cooled by the bearings lead to the ends of the rolls being somewhat cooler than the centre, it is possible to make use of this effect of thermal camber. The thermal camber in a roll of 17 inches diameter amounts to 0.06 mm for 10°C (18°F) difference in temperature. The roll surfaces

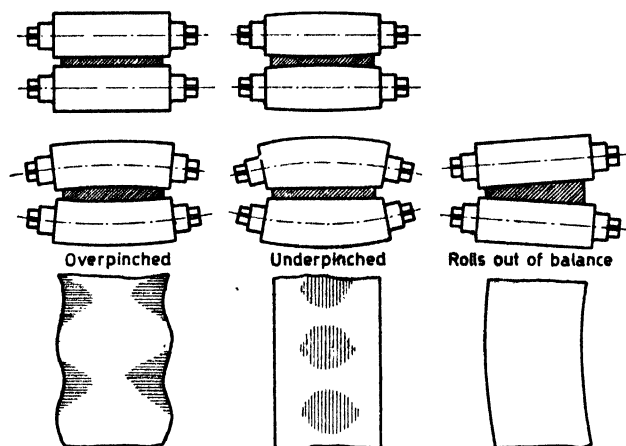


Fig. 209. Effect of roll camber on shape of sheet.

deteriorate in use and after a time must be reground, this being done in a roll-grinding machine provided with arrangements to generate the required camber.

#### e. Rolling of magnesium

Owing to its hexagonal crystal structure, the ease of deformation is less with magnesium than with aluminium alloys. Hot rolling is carried on at a temperature of 350° to 450°C (662° to 842°F) according to the alloy, and the roll barrel lubricant used, according to Swiss Patent 216207, British Patent 551353 and U.S. Patent 2349395, is much more sparingly applied than with aluminium. At thicknesses less than  $\frac{3}{4}$  inch, the rolls are usually not lubricated, as an oil film which is usually not spread uniformly will give rise to uneven deformation of the stock and may cause cracks across the direction of rolling. It has also been proposed to use bituminous compounds as rolling lubricants. Instead of the cold rolling ordinarily applied to aluminium, magnesium is rolled hot, always over 250°C (482°F), nearly to the finished gauge, at which the rolling temperature is held as close as possible to 200°C (392°F). The sheet blanks are generally reheated in annealing furnaces, given one pass only, and at once put back into the annealing furnace for a reheat. To improve the surface quality, the magnesium blocks are often clad with a thin pure aluminium sheet, which permits the same rolling conditions to be followed as for aluminium.



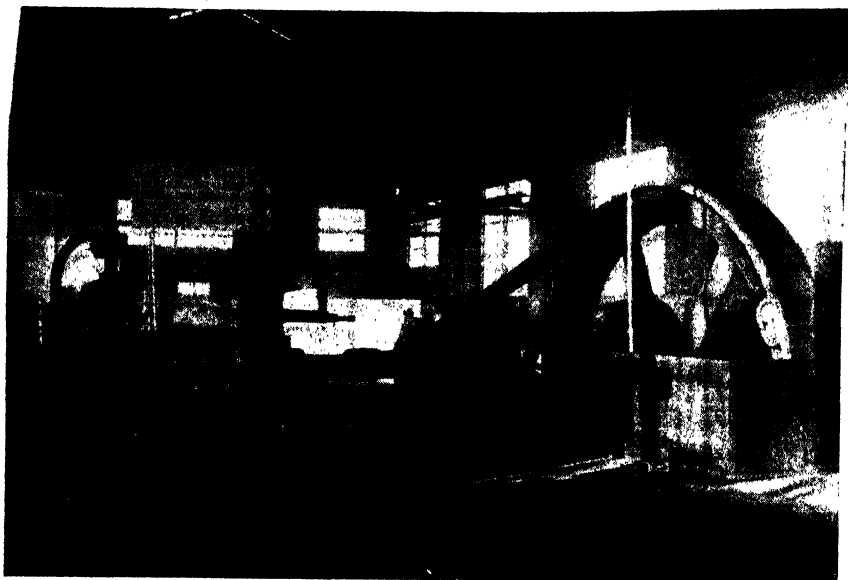


Fig. 210. Small cogging mill for rolling of aluminium wire-rod.

*f. Rod rolling*

For the production of light metal sections and rods, either the rolling process or the extrusion process, described later, may be used. The rod rolling process is mainly used for the production of wire rod for cable manufacture. The type of mill used is similar to that used generally in copper wire manufacture. In cases where both copper and aluminium

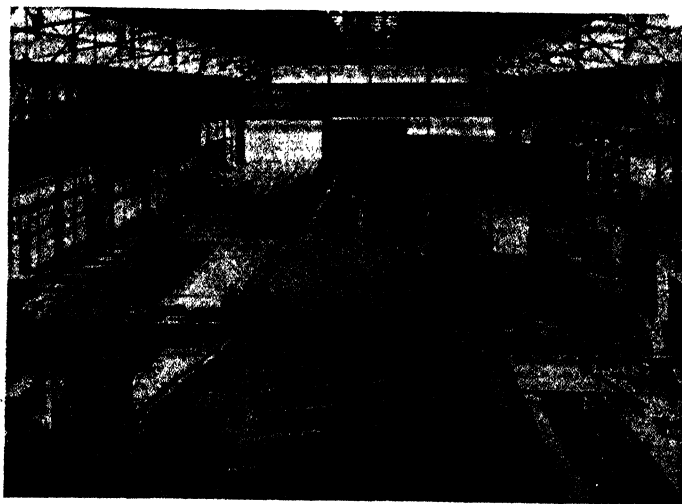


Fig. 211. Continuous rod mill (Demag).

are rolled on the same mill, a careful cleaning of the whole plant of copper particles before turning over to aluminium is essential. As, in spite of this, some contamination of the rod is unavoidable, the rod must be pickled in cold 30% nitric acid to free it from copper, otherwise dangerous corrosion may occur due to local galvanic couples.

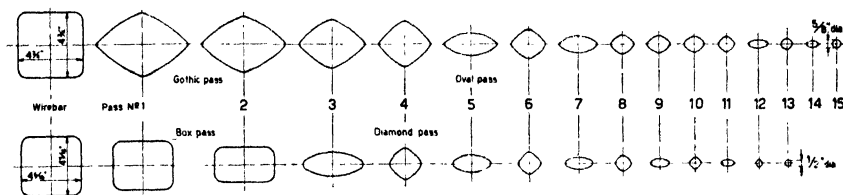


Fig. 212. Roll pass design for aluminium rod mill.

Note: The diamond pass is more usually called square.

The rolling of aluminium wire rod can be done on single mills, as shown in Fig. 210, or continuous mills, as in Fig. 211. In both cases, cast wire bars  $4 \times 4$  inches up to  $4\frac{3}{4} \times 4\frac{3}{4}$  inches in cross section and 3 to 5 feet long, weighing from 60 to 130 pounds are processed. Customary roll pass designs for aluminium rod rolling are shown in Fig. 212. For Aldrey (Silmalec—Al-Mg-Si) production, where a cold reduction of over 90% is required, a wire rod of about  $\frac{5}{8}$  inch is rolled, while for pure aluminium the size of wire rod is  $\frac{1}{4}$  to  $\frac{1}{2}$  inch.

The wire bars are heated to  $400^{\circ}$  to  $500^{\circ}\text{C}$  ( $752^{\circ}$  to  $932^{\circ}\text{F}$ ) for hot rolling. The optimum electrical conductivity is obtained in pure aluminium with a rolling temperature of  $425^{\circ}$  to  $475^{\circ}\text{C}$  ( $797^{\circ}$  to  $887^{\circ}\text{F}$ ). The rolling speed is 350 to 550 feet per minute in the roughing and 900 to 1300 feet per minute in the finishing stands. The output of a small mill comprising one roughing and one finishing stand is about 4 tons a shift, that of a high-capacity continuous rod mill would be about 80 tons in an 8-hour shift.

## CHAPTER VIII: EXTRUSION

### 1. INTRODUCTORY

The good hot-working properties of the light metals make possible the production of an almost unlimited variety of shapes by the extrusion process. Fig. 213 illustrates a collection of sections extruded in aluminium alloys, the biggest section (lower right) being composed of several parts dovetailing together. The optimum extrusion temperature varies between  $300^{\circ}$  and  $550^{\circ}\text{C}$  ( $572^{\circ}$  and  $1022^{\circ}\text{F}$ ) according to the alloy. Compared with section rolling, the extrusion process has the outstanding advantage of much lower tool charges; even a very large and complicated extrusion die would not cost more than perhaps £100, whereas for rolling even a simple Tee, a complete set of rolls costing many hundreds of pounds sterling would be required. There is a further advantage in regard to the time required for tool changes; in the case of extrusion there is only a die change to be made which takes but a very few minutes, while to change a set of rolls takes hours. For reasons such as the above, rolled sections are only produced where there are large quantities required, while smaller quantities, which may be as low as 20 or 30 pounds, are produced by extrusion, and in this process the requirements of the consumer can be closely met. Complicated sections to be produced by rolling may not be adaptable to being rolled in one piece, but might have to be rolled in several separate sections to be afterwards assembled by riveting or welding.

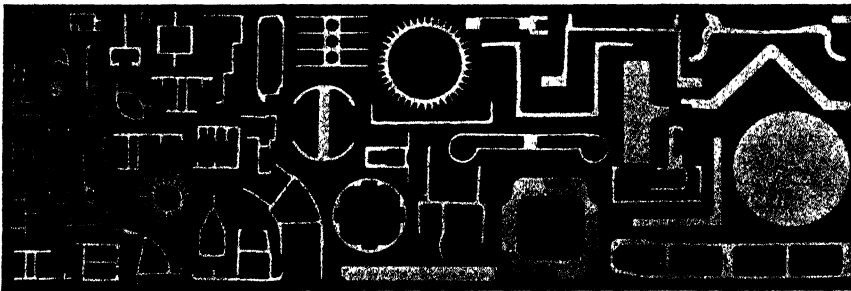


Fig. 213. A collection of extruded sections.

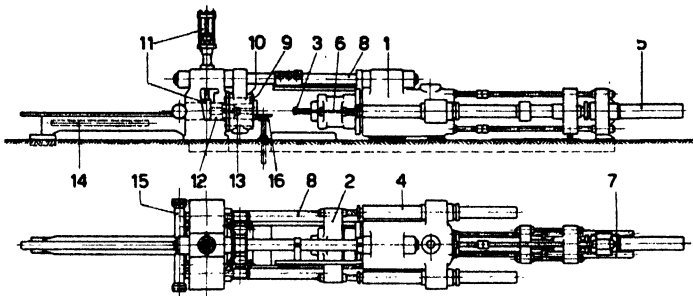


Fig. 214: General arrangement of an extrusion press (piercing type).

- |                          |                              |                           |                                  |
|--------------------------|------------------------------|---------------------------|----------------------------------|
| 1 Main cylinder and ram. | 5 Piercing cylinder.         | 9 Container.              | 13 Die.                          |
| 2 Main crosshead.        | 6 Tube mandrel.              | 10 Container housing.     | 14 Hydraulic die-shifting table. |
| 3 Plunger                | 7 Piercing return cylinders. | 11 Hydraulic wedge slide. | 15 Hydraulic shear.              |
| 4 Main return cylinders  | 8 Tie rods or columns.       | 12 Bolster.               | 16 Billet cradle                 |

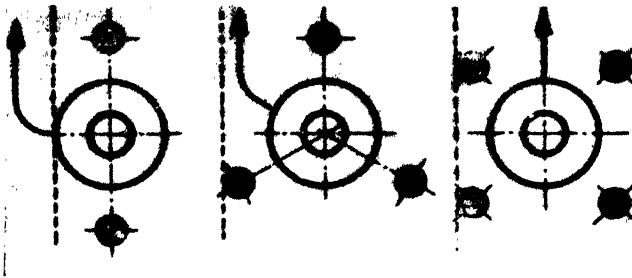


Fig. 215. Arrangement of columns or extrusion presses.

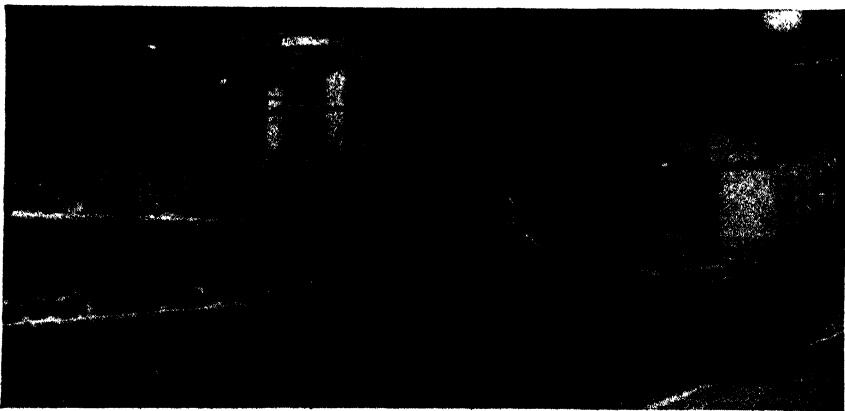


Fig. 216. 2500 ton extrusion press (The Loewy Engineering Co., Ltd., London).

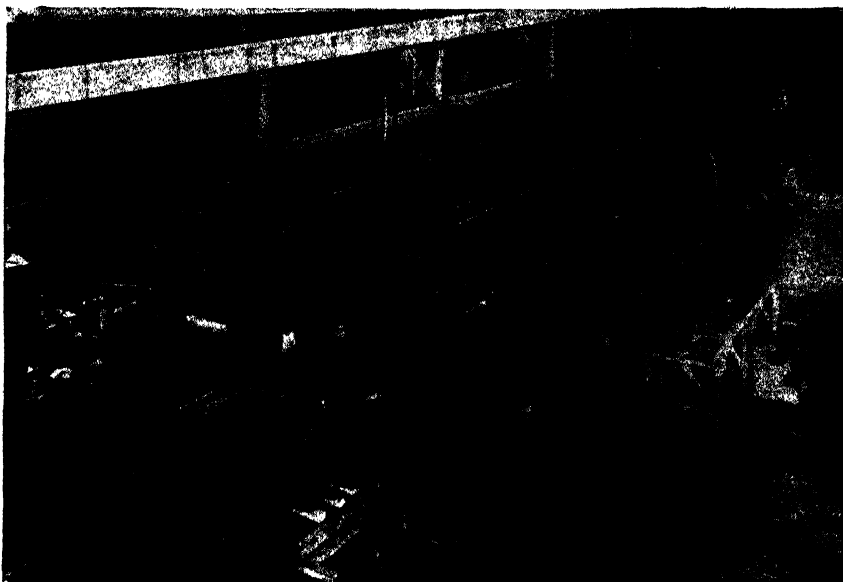


Fig. 217. 4-column extrusion press (Fielding & Platt Ltd., Gloucester).

Extrusion presses are classified according to their design and operating principle as under:

- a. Process of operation —  
Section or tube presses  
Direct or indirect presses
- b. Arrangement of press —  
Horizontal or vertical presses
- c. Power supply —  
Mechanically or hydraulically operated presses.  
For light alloys hydraulic operation is in general use owing to the wide range of speeds and close control required.

Referring to Fig. 214 which shows the details of the construction of a horizontal section and tube press, we can distinguish:

- a. The hydraulic parts;
- b. The extrusion parts proper, comprising the container and extruding stem or plunger;
- c. The profiling parts, comprising the die and related parts.

Extrusion presses are built with 2, 3 or 4 tie-rods or columns as shown in Fig. 215. The best for accessibility is the 2-column press though the changing of the container by lifting with a crane is easiest in the 4-column press. Fig. 216 shows a 3-column 2500 ton press, and Fig. 217 a 4-column 5000 tonner. Smaller presses up to 1000 tons are in some cases built vertical,

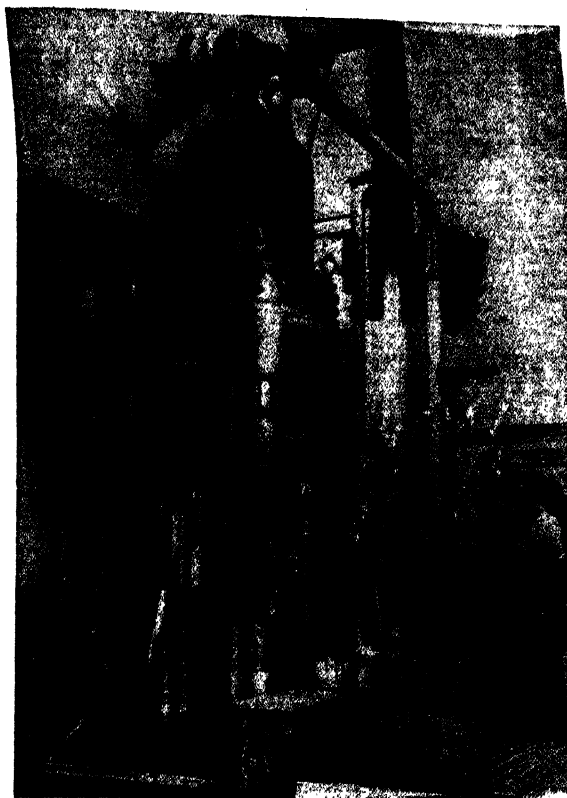


Fig. 218. 1000 ton vertical extrusion press (Aluminium Menziken A.G., Switzerland).

as shown in Fig. 218, an advantage of this arrangement being the smaller floor-space required. Vertical presses must either be raised on a gantry or the press must be arranged to deliver the section below floor level, which is often found to have disadvantages.

## 2. HYDRAULIC PARTS OF AN EXTRUSION PRESS

In tube presses, the pressure cylinders are two in number, the main cylinder which actuates the extrusion plunger, and the piercing or mandrel cylinder, which actuates the tube mandrel. Cooperating with both these cylinders there are one or more return or draw-back cylinders. If rods or

sections are extruded, the main and mandrel cylinders are valved to work together, with which arrangement the extrusion thrust is the sum of the two. A very important part of the hydraulic system are the control valves, as an accurate control of the speed of extrusion is essential with aluminium. To achieve this, a type of needle valve is used, which is generally located near the delivery end of the press so that the operator can observe the section as it leaves the press.

For indicating the speed of extrusion, modern presses are provided with speed indicators, working off the extrusion ram, which indicate the speed of the ram. From the ram speed and the ratio of the container area to the die orifice area, the speed of the section leaving the die can obviously be calculated. This type of speed indicator can be actuated by hydraulic, electric or mechanical means.

## 3. EXTRUSION PARTS OF THE EXTRUSION PRESS

The extrusion parts proper which operate on the stock are the highest stressed components of the press. For extruding aluminium alloys, pressures up to 100 tons per square inch are required on the metal, and since it is plastic at a high temperature, the metal behaves like a liquid under pressure. The pressure is thus substantially equal in all directions, and therefore an internal pressure is exerted on the container. In addition, the container is subjected to the force of friction during extrusion from the movement of the metal inside it. The container is therefore usually made of a composite construction, the inside liner being made from a high chrome-

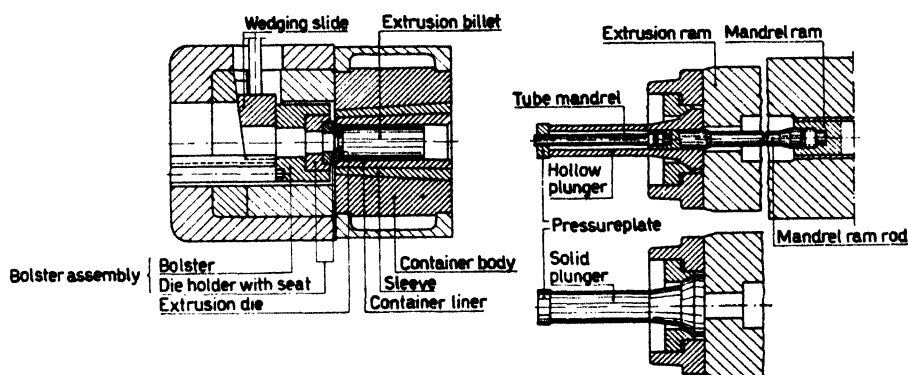


Fig. 219. Arrangement of extrusion press container and plunger.

tungsten steel, while the body of the container is usually of forged mild steel. The duration of one extrusion operation is from 1 to 30 minutes according to the speed of the press, the section of the extrusion and the size of the billet, during which time the temperature of the container must remain constant. To ensure this, the container must be provided with suitable means for external heating, which must heat the whole peripheral surface of the container uniformly, and be easily controllable. These conditions are best obtained with electrical heating, for which ordinary resistance heaters may be used, accommodated in the space between the container body and the housing, or in holes drilled in the container body, while induction heaters have also been proposed. The extruding plunger which transmits the force from the hydraulic cylinder to the container bore, is of course subject to intense compressive loading and must therefore be made of a high-strength steel. Since the diameter of the container bore changes owing to the different working temperatures used and due to wear in use, a small clearance for the plunger would not be practicable, and therefore a dummy or pressure plate is inserted in the container in

front of the plunger, which plate must be a close fit in the container and is made of a heat-resisting alloy steel. Table 29 gives the pressure in the container required for extruding various alloys to a section 1/8th inch thick, the effect of the billet length also being shown. Owing to the friction of the extrusion billet in the container, the pressure required varies according to the length of the billet. With alloys difficult to extrude, a short billet is therefore generally used. Lubrication of the extrusion billet with oil and graphite for the purpose of reducing the friction is not permissible as this would give rise to contamination of the extruded section by traces of the lubricant. In tube extrusion, however, lubrication of the extrusion mandrel must not be omitted. For this purpose an oil or water emulsion of colloidal graphite is used. The tubes are examined carefully for residual lubricant, and this is removed either by wire brushing, or chemically by immersion in a solution of 20%  $\text{H}_2\text{SO}_4$  + 3%  $\text{CrO}_3$  in water at 50°C (122°F).

TABLE 29  
EXTRUSION OF SECTIONS

Extrusion temperature °C °F	Material extruded. Alloy types				
	Pure al. 450—500 842—932	Al-Mg-Mn 450—500 842—932	Al-Si-Mg 450—500 842—932	Al-Cu-Mg 380—460 716—860	Al-Mg7 380—420 716—788
Max. extrudable section for a container pressure of 16 tons per sq. inch in a container of 16 inches diameter	$\frac{5}{16} \times 4$ inches	$2 \times 4$ inches	$1\frac{1}{4} \times 4$ inches	$3 \times 4$ inches	$4 \times 4\frac{3}{4}$ inches
Container pressure with a section thickness of 1/8th inch, billet diameter of 8 inches and length of 32 inches	19—25 tons per sq. inch.	44—63 tons per sq. inch.	32—47 tons per sq. inch.	54—70 tons per sq. inch.	76—95 tons per sq. inch.
Ditto with a billet length of 16 inches	15—20	36—51	25—38	44—57	60—76

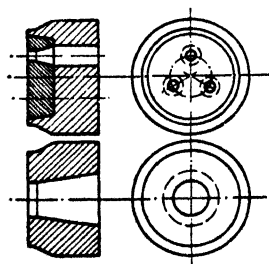


Fig. 220. Extrusion dies.

#### 4. DIES

The shape of the section is formed by a die which is held up against the container at the outgoing end (Fig. 220), and in which the die orifice is cut very accurately to give the exact shape required. The flow of the metal in the die gives rise to conditions of heavy wear and stress, and the die must therefore be made of special hot die steel. For



reasons of economy, use is made of a composite assembly in the die, as in the container, and only the central portion with the high stressed working

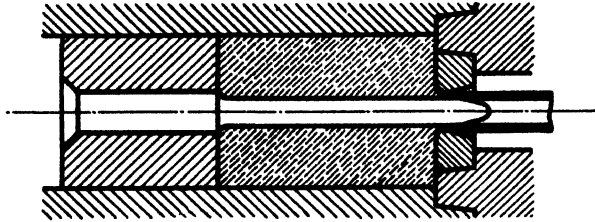


Fig. 221. Tube extrusion with floating mandrel.



Fig. 222.

Section extruded from a compound die.

tightly into the container on its chamfered bearing surface, so that the metal is free to extrude only through the orifice. The closing and opening of the die is done in modern presses by hydraulic operation, the bolster being mounted on a hydraulically operated shifting slide. The die holder is carried

in the bolster, and into it the die itself is finally inserted. The bolster and die assembly are held tight against the container by a wedge or locking slide, which also is hydraulically actuated on modern presses. The locking slide is withdrawn after the completion of an extrusion operation, and the billet end is pressed out by

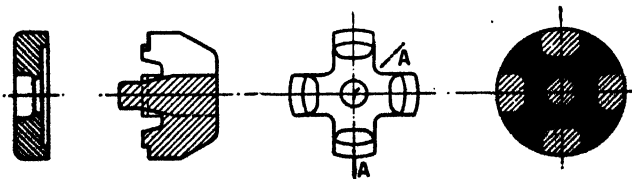
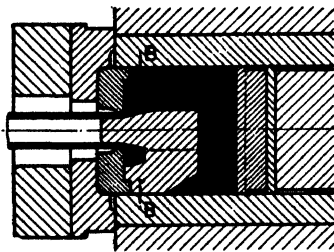


Fig. 222a. Compound die for tube extrusion.

the plunger, forcing out also the die and bolster on its slide, following which the billet end is separated from the die and the section, the section then being pulled out of the die.

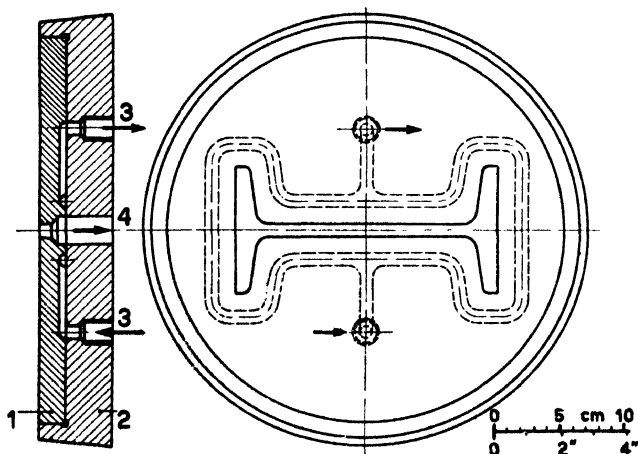


Fig. 222b. Water-cooled extrusion die.

Solid billets are used for the extrusion of rods and sections, while for tubes, cored billets are used as in Fig. 221, which are extruded over a short mandrel the metal being extruded in an annular shape between the mandrel and round die. In so-called tube presses, the mandrel is carried on a subsidiary mandrel ram, but ordinary rod presses which have no mandrel ram can also be used for most tube jobs, using cored billets, the tube mandrel being carried in a special long pressure plate. For the production of tubes and hollow sections, a compound die is frequently used (Fig. 222a). Fig. 222 shows a section extruded from such a die, which permits the possibilities of this process to be appreciated. This type of hollow extrusion can only be carried out with certain softer alloys, such as Al-Si-Mg alloy, and pure aluminium.

The speed of extrusion is dependent on the composition of the alloy, the temperature required for extrusion and the heat generated in the flow of the metal through the die. It has been found possible by the adoption of suitable water-cooling of the die (Fig. 222b) to increase the speed of extrusion by 25 to 50 %, especially with the Al-Cu-Mg alloy.

## 5. INDIRECT EXTRUSION

Beside the direct extrusion process described above, the inventor of the extrusion press, Dick, also developed an indirect extrusion process <sup>1</sup>

<sup>1</sup> Described also by Genders, Journ. Inst. Metals, 1921, 2, (XXVI).

(Fig. 223). In the direct extrusion process, the billet is moved by the action of the plunger gradually along the container through the die, but in the indirect process the billet does not move relative to the container, and the die, which is located at the end of the hollow plunger, is itself advanced

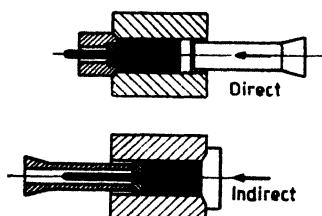


Fig. 223.

Direct and indirect extrusion.

gradually into the billet. The result of this is that in this process, a smaller degree of deformation of the metal takes place and consequently a lower pressure is required. The disadvantages lie in the complexity of the press, the weakness of the plunger through being hollow, the limitation of section size and the smaller deformation of the metal. The flow of the metal in the direct and indirect processes is shown in Fig. 224.

A large difference in cross-sectional area between the billet and the extruded section itself implies a high degree of deformation of the metal, which in the direct extrusion process gives rise on heat-treatment to a tendency to grain growth in the outer zones of the extruded rod or section. This is particularly liable to occur at the last end of the rod to be extruded, as the metal has suffered the greatest deformation here. In contrast to this, the indirect extrusion process has the advantage that the entire volume of metal is uniformly, though more lightly, deformed from the beginning to the end of extrusion. Thus where the difference in cross-sectional area between the billet and rod is great, i.e., where a small section is extruded from a large container, the indirect extrusion process has the advantage not only of a lower pressure, but also the avoidance of coarse-grained superficial zones, and this, as is predicted by AHEARNE HERON<sup>1</sup>, is likely to arouse interest again in the future in this method of extrusion.

As already mentioned, hydraulic presses are used for extruding aluminium. Direct pumps were much used in the early days (Fig. 225), but today a central hydraulic system serving several presses is more usual, the fluctuating demand for water being met from a hydraulic accumulator. Instead of the earlier gravity loaded accumulators we now find air-hydraulic accumulators used to an increasing extent. The latter have the advantage of a smaller floor space, greater safety and freedom from

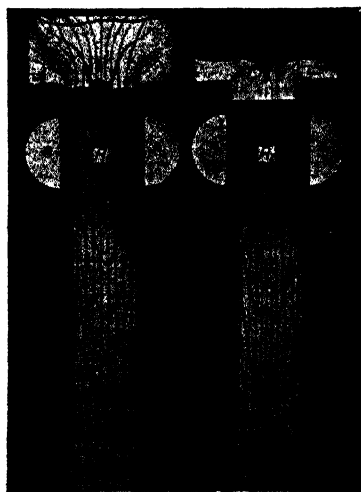


Fig. 224. Flowlines in extruded rods.  
Left: indirect; Right: direct.

<sup>1</sup> *Metal Ind.*, Vol. 68, No. 20, p. 389 (1946).

pulsations. For the idle portion of the working stroke, there is an arrangement for automatic change-over to low pressure water at 140 pounds per sq. inch supplied from a prefilling air vessel, instead of the high pressure water at 3000 to 5000 pounds per sq. inch. Fig. 226 shows a hydraulic pressure installation,

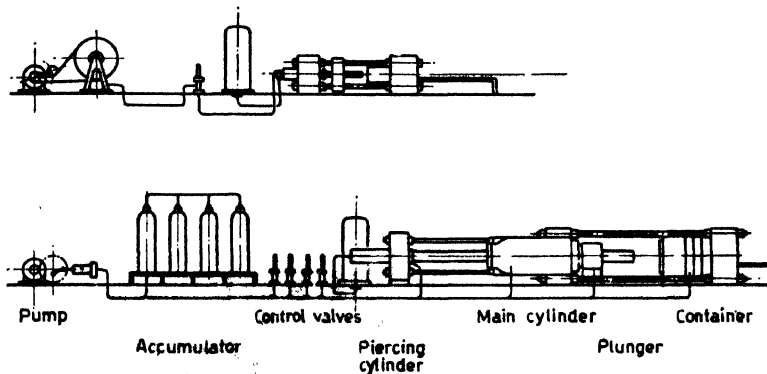


Fig. 225. Arrangements of pumps and accumulators for hydraulic extrusion presses.  
Above: direct pumps. Below: air hydraulic accumulator system.

in which the water and compressed air bottles can be seen in the background. To restrict the drop of pressure, a volume of compressed air 10 times that of the water in the accumulator is used in practice. Instead of the older belt-driven pumps, gear-driven pumps with direct motor drive are used in modern practice. The higher cost of the gear drive is offset by lower maintenance costs, higher availability and smaller floorspace.

## 6. EXTRUDED SHAPES

It was stated at the beginning of the chapter that almost any shape of section could be produced by extrusion, but consideration must be given to the configuration of the section in relation to the difficulties of making the die and of producing the section. Fig. 227

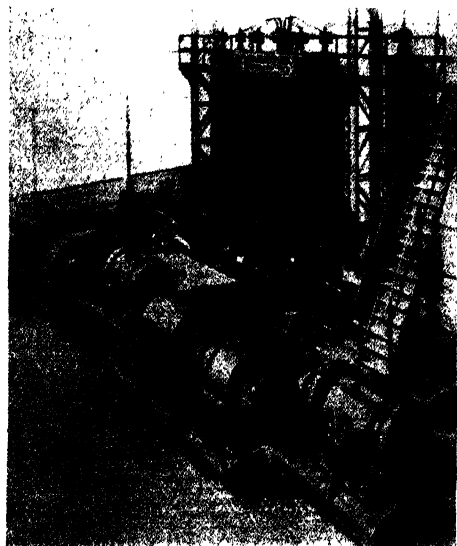


Fig. 226. Hydraulic pump installation with air bottle accumulator (Hydraulik, Duisburg).

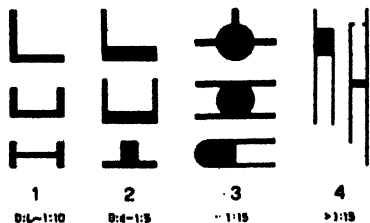


Fig. 227. Extruded sections in 4 groups of ascending difficulty.

D, d = wall thickness. L = leg length.

shows 4 groups of extruded section. All normal sections, like those handled by the brass industry, can be extruded without difficulty, and so generally can all sections with a leg-length:thickness ratio in the section of not more than 10:1, with uniform thickness, and with a ratio of section area:container

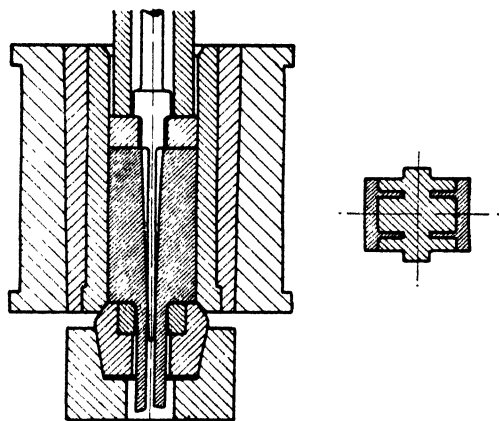


Fig. 228. Extrusion of tapered sections.



Fig. 229. Cross section of rod with coarsely crystalline peripheral zone.

area of 1:40 maximum. Sections of the second group with differences in wall thickness of up to 1:5, are more difficult to extrude satisfactorily, as the section will tend to extrude quicker through the die where the wall thickness is greatest owing to the smaller friction in this region. These two groups are, however, by no means difficult to extrude. Much more

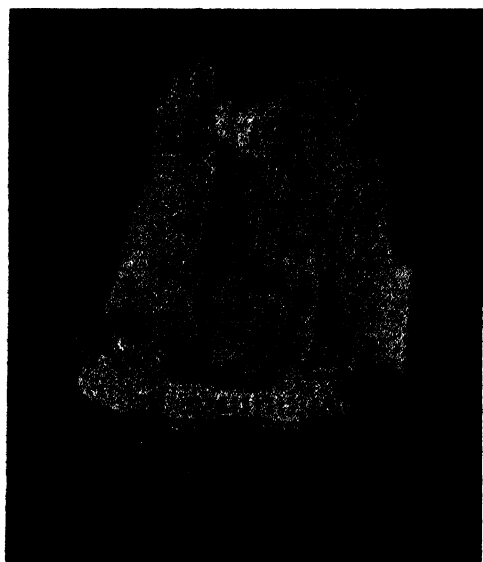


Fig. 230. Rod showing fibrous fracture.

difficulty attaches to group 3 sections, with a wall thickness ratio of 1:5 to 1:15, in which special technique and very slow extrusion are essential. The 4th group with a very high ratio of wall thickness to leg-length of 1:15 or more call for a very special construction of the die. Such sections frequently have to be extruded with an open shape, and to be closed by a subsequent drawing operation. Hollow sections have not been included in this grading. These can only be produced by special compound dies (Fig. 222a). In aircraft construction, tapered sections are often wanted, as for spar booms.

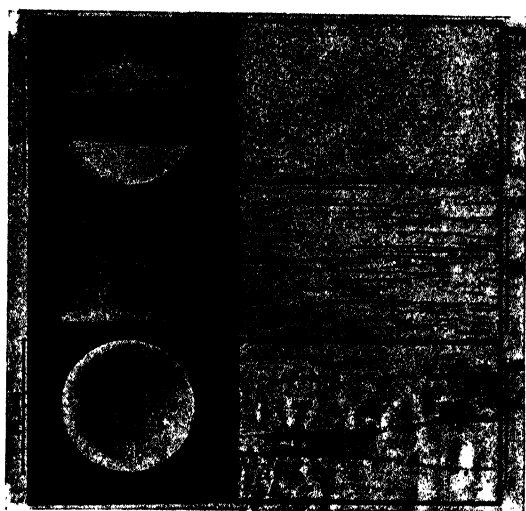


Fig. 231. Cause of fibrous fracture.

as in Fig. 229. The tensile properties are not impaired by this, if the grain-growth is kept down within reasonable bounds, by the adoption of suitable extrusion conditions. Coarse recrystallisation of the outer layers can only be avoided with certainty by cold drawing after extrusion and before heat-treatment. Fracture tests on the larger sized extruded sections, in Al-Cu-Mg alloy (Duralumin or Avional) often show fibrous fractures as in Fig. 230, which at first sight give the impression that flaws exist in the material. It can be seen from the section shown in Fig. 231 that this is not really the case, but that the material is sound. The cause of this fibrous structure is segregations which cannot be avoided when large billets are used, and these on extrusion are elongated, as shown, into long fibres. The structure is also influenced by the extrusion temperature and speed. At high temperatures, a preferred orientation of the crystallites with the cube edges (100) parallel to the extrusion axis develops, resulting in a definitely fibrous fracture. Under more normal extrusion conditions a (111)-texture develops, corresponding to an orientation of the cube diagonals parallel to the extrusion axis, which gives a fracture of the normal non-fibrous type.

Comparing the mechanical properties of extruded Avional S (Duralumin) bars with those of bars of the same material extruded and drawn before heat-treatment, it can be seen from Table 30 that the bars heat-treated as extruded have the higher properties, which is ascribable to the so-called extrusion effect. The X-ray diffraction photograph Fig. 232 gives the explanation of this phenomenon.

These are either produced from thick sections by milling, or in the case of simple tapers they can be extruded direct to the required shape by using a tapered extrusion mandrel, as in Fig. 228.

## 7. EXTRUSION DEFECTS

Owing to the greater flow in the outer layers of the section, subsequent heating of the same, as in heat treatment, gives rise to grain-growth in the outer portions, so that a coarse-grained outer zone is often found

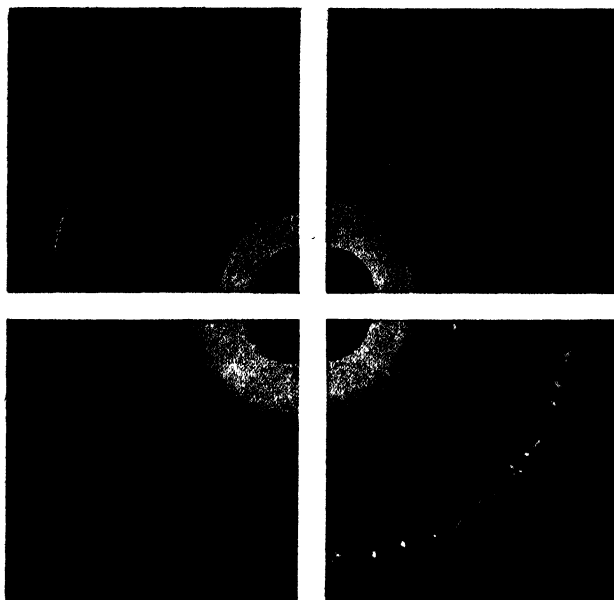


Fig. 232. Effect of cold drawing on the recrystallisation of extruded rods.  
(X-ray diffraction patterns).

Upper left: extruded at 460°C (860°F).

Lower left: extruded at 460°C (860°F) and drawn.

Upper right: extruded at 460°C (860°F) heat-treated at 500°C (932°F) and quenched.

Lower right: extruded at 460°C (860°F), cold drawn, heat-treated at 500°C (932°F) and quenched.

TABLE 30

EXTRUSION EFFECT

Avional S bars, 3 in. diameter.	0.2% Proof Stress		Tensile Strength		Elongation %
	Tons/sq. in.	lb./sq. in.	Tons/sq. in.	lb./sq. in.	
Extruded & heat-treated . . . .	23.8	53000	35.1	78000	15.1
Extruded, drawn & heat-treated	20.6	46000	28.2	63000	16.8

At a solution heat-treatment temperature of 500°C (932°F), the extruded material shows no indication of recrystallisation, but extruded and drawn material exhibits complete recrystallisation. By the latter process, the preferred orientation of the as-extruded crystal structure in the longitudinal direction giving enhanced properties in this direction, is randomised and this is followed by some decrease of strength and proof stress.

## CHAPTER IX : FORGING

### 1. GENERAL

In fabrication of metal direct to finished shape, or literally "chipless forming", the forging process comes in importance after casting. In the U.S.A., the proportion of forgings to total aluminium manufactures increased from 1½% in 1939 to 11% in 1942, which indicates the increasing importance of forgings. The reason for the increased usage of forgings lies in their superior quality compared with castings, due to the plastic deformation imposed in their production (p. 167). In forging we distinguish between free forging under the hammer or forging press without dies, and forging in dies, or drop forging. The superior accuracy of shape obtainable with drop forging in dies involves a higher cost, so that this can be economically justified only for a sufficiently great number of pieces. In the selection of forging alloy, the resistance to deformation as given in Table 28 must receive consideration. Among the strong alloys, the Al-Si-Mg alloys are the most easily forged, and are therefore used for preference.

Owing to the superior plasticity of extruded bar stock, this raw material should be used as far as possible. Cast blocks for forging are only utilised when the weight of the piece is too great for extruded stock to be used. As cast blocks are susceptible to cracking, their initial deformation must be carried out with caution, and, to homogenise the cast structure, the blocks should be heated for 8 to 24 hours at the highest safe temperature, this,

in the case of heat-treatable alloys being the maximum permissible solution heat-treatment temperature. For cast alloys, this is 20°C (36°F) below the solution heat-treatment temperature for wrought material given in Table 27. In the forging operation, it is important that forging should not be carried on below the minimum permitted temperature given in the same table, else there is a danger that internal cracks may develop in the forgings as shown in Fig. 233. To retard loss of temperature in forging, the dies should be heated to about 250°C (500°F).



Fig. 233. Forging cracks due to too low a forging temperature.



## 2. FORGING PLANT

From a consideration of the kinematics of the different forging machines as shown graphically in Fig. 234, and seeing that the resistance to deformation in light metals rises sharply with increased speed of deformation, it is evident that slow speed presses are to be preferred to hammers. On

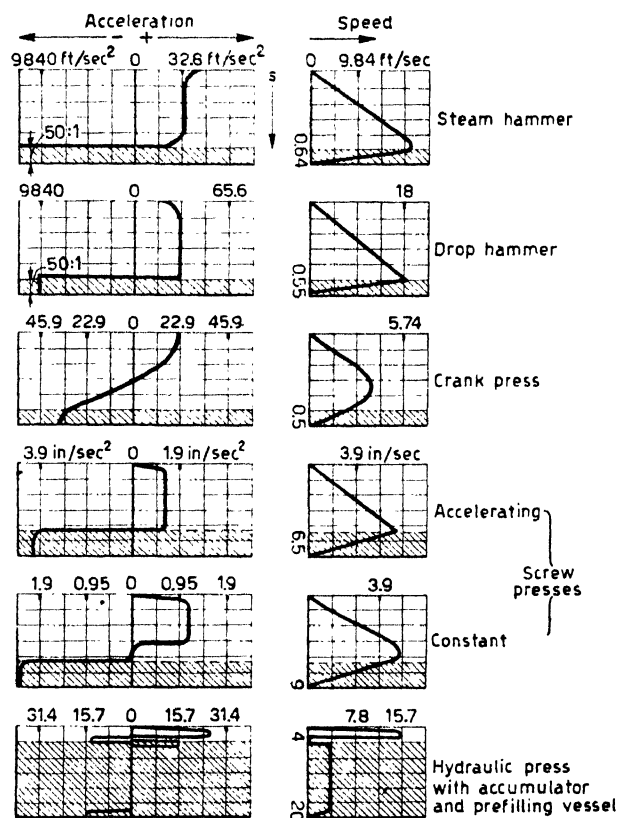


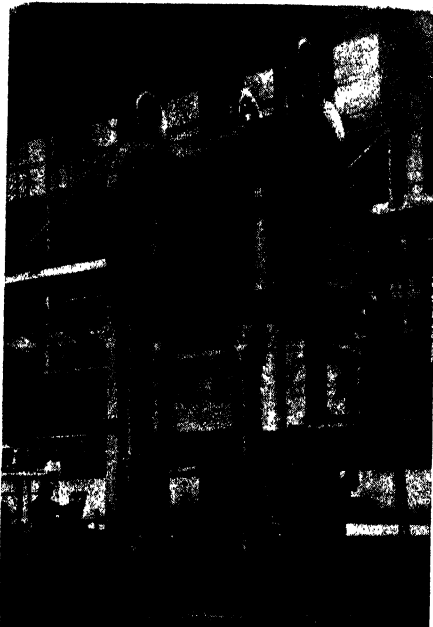
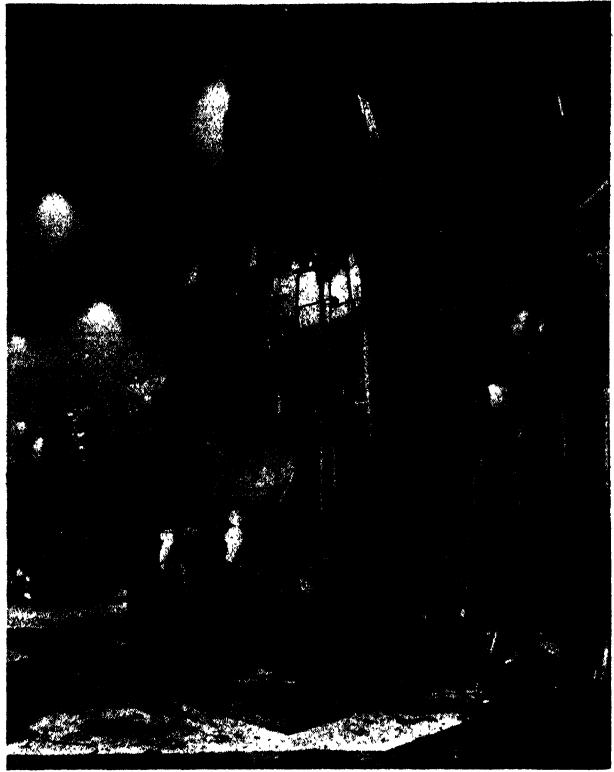
Fig. 234. Kinematic characteristics of forging machines.

the other hand, however, the blows of a drop hammer cause the metal to fill the die better, so that for difficult or intricate pieces in which a large displacement of metal is required, the use of a drop hammer is preferable to a press. The height of fall of a drop hammer should not exceed 3 feet; thus heavier hammers than are used for forging heavy metals are necessary. For the drop forging of propellers and crank-cases for aircraft engines, the modern practice is to use drop hammers with a total weight of tup of 20 to 30 tons, whereas a forging press to do the same work would have to be of 30000 tons capacity. Fig. 235 shows a 16 ton steam hammer

Fig. 235.

16 ton steam hammer by  
Chambersburgh Engineering  
Co. (High Duty Alloys Ltd.)

for the forging of propellers, and Fig. 236 a 12000 ton forging press. In the die forging of complicated pieces, these are often rough forged or cogged down under an open hammer in the first place, and finally struck to size in the dies. In an alternative process, a chill cast blank or dummy of approximate shape and size is forged to size in a forging press. This method has been used in the manufacture of propel-



lers for military aircraft, for example. One advantage of drop-forging in dies is the greater accuracy of the product that may be obtained, such that, for instance, in the production of propellers, the loss of metal in machining may be cut down by half compared with forged propellers produced under an open hammer. A disadvantage of the press forging process which causes slower operation of the press lies in the comparatively rapid cooling of the die, which not infrequently necessitates a second heating of the work. Counter-blow hammers (Fig. 237) have been recently

Fig. 236. 12000 ton forging press — Loewy Engineering Co. Ltd.

used with success and these work with less vibration and with double impact energy for a given weight of tup. In friction screw presses, one type has a varying speed of stroke. In these the driving wheel descends with the tup, and in doing so engages with the friction disc at an increasing diameter, by which its peripheral speed is increased (Fig. 238). In another type of screw press, the velocity is uniform. Fig. 239 shows such a press in which the screw is driven by a motor-driven profiled roller engaging in grooves in the driving wheel. This arrangement has the advantage of reduced rate of wear. In die-forging presses, the whole surface of the piece

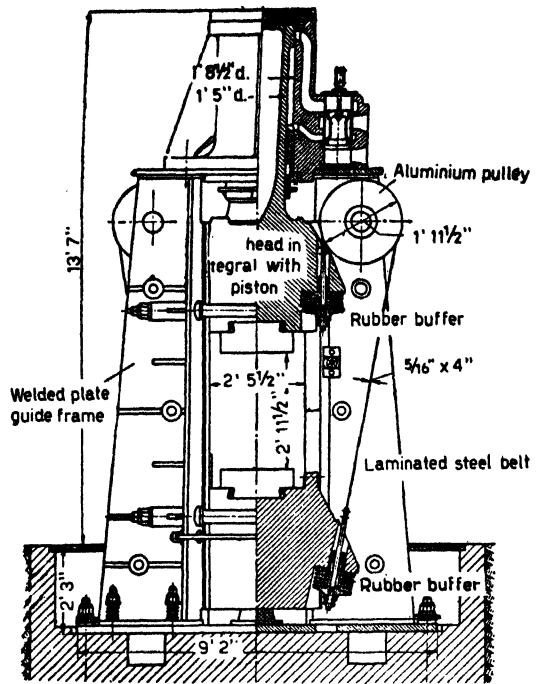


Fig. 237. Counter-blow hammer (Eumuco).



Fig. 238.

Friction screw percussion press with variable velocity of stroke (Schuler).

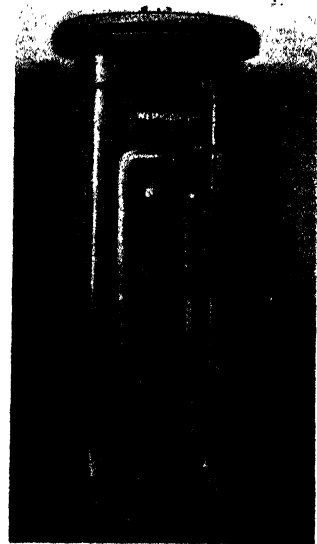


Fig. 239. Friction screw percussion press with constant velocity of stroke (Weingarten).

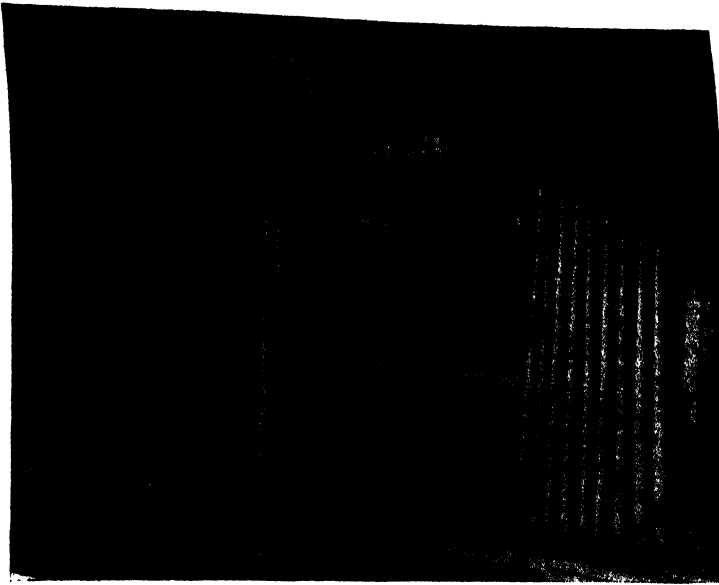


Fig. 240. Forging rolls (Eumuco Ltd., London).

is under pressure at one time. According to the nature of the material, and the working temperature, the forging pressure required for light alloys, as shown in Table 28, lies between  $1\frac{1}{4}$  and  $6\frac{1}{4}$  tons/sq. in. (2800 and 14000 lb./sq. in.) and for large forgings, considerable force must be developed in the larger presses. In this it differs from rolling, in which only a very limited part of the piece is deformed at one time, so that only a fraction of the total force that would be necessary for die forging in a press, is required for rolling. For this reason, forging rolls, as shown in Fig. 240, are used for the cogging down of large forgings. At the commencement of the operation, starting with round extruded bar stock, the rolls are opened wide. As the forging progresses, these are gradually screwed down to diminish the gap, so that the whole forging process is subdivided into a multiplicity of single operations.

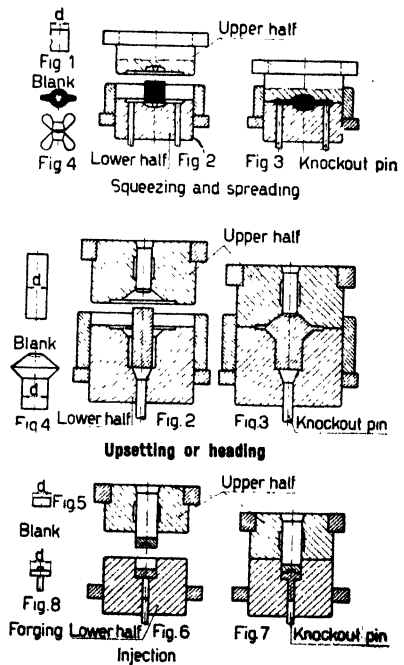


Fig. 241. Methods of shaping in forging.

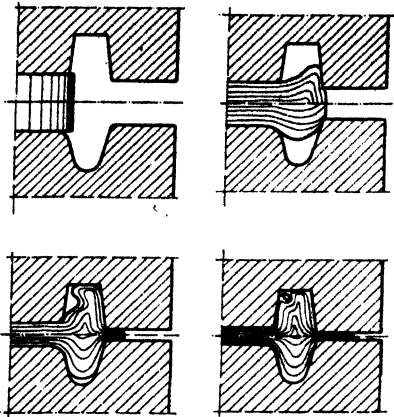


Fig. 242. Flow of metal in forging dies.  
Top die: sharp-cornered. Bottom die: rounded.

rounded corners. The illustration shows how a sharp-cornered die gives rise to an unsatisfactory course of the fibre, incomplete filling of the die, and in consequence of this, a tendency to formation of laps, seams, or double metal. Examples of the effects of quite small faults in the die,

### 3. DROP FORGING DIES

In drop forging, there are the shallow spreading, and deeper heading, and injection dies (Fig. 241), the first named requiring least force and the last named the greatest. The high resistance to deformation and the notch-sensitivity of aluminium alloys demand a careful design of the die, and in plain forging, a well rounded hammer. Fig. 242 shows the flow of the metal in a forging operation, the upper half of the die being shown with sharp corners, and the lower, as is necessary for aluminium, with well

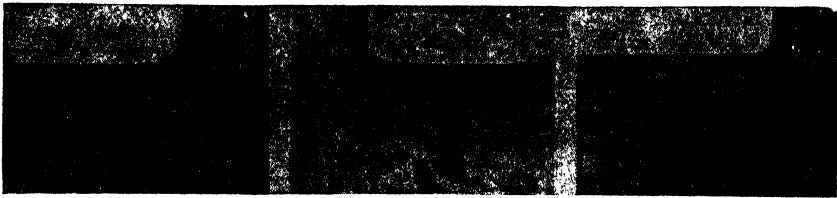


Fig. 243. Effect of incorrect shape of die on course of fibre.

particularly of sharp-cornered junctions, are illustrated in Fig. 243. The location of the flash and gutter of the die, into which the excess metal is squeezed out, must be watched with special care. Fig. 244 illustrates a separation in a forging caused by a sucking action taking place by the flash that has been forced out to the gutter, due to an incorrect location of the flash.



As far as possible, forging dies for light metals, as shown in Fig. 245, should be given a greater draft than for heavy metals. Furthermore they should be very smooth, preferably polished, so that they offer a minimum of frictional resistance to the flow of the metal. For die lubrication, an oil which leaves no residue on vapourisation (as for

Fig. 244. Forging defect due to incorrect location of flash.

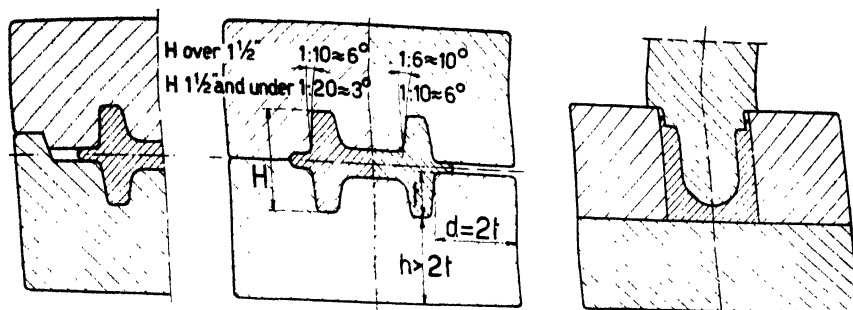


Fig. 245. Dies for forging press.

rolling) is the most suitable, and if necessary colloidal graphite may be added. In designing the die, its walls should not be made too thin. As the illustration shows, a thickness of steel at any point equal to at least twice the depth of impression should be allowed. The use of die inserts, which are made use of for cheap drop-forgings in steel, are not in general to be recommended. To ensure a good life for the dies as well as to obtain a correct fibre structure in the forging and complete filling of the die by the light metal, sharp corners should be avoided in the form of the piece, and generous radii should be given at the corners. If sharp-cornered impressions cannot be avoided, the die should not be heat-treated to the maximum strength, and it is preferable to limit the strength to 75 to 85 tons per sq. inch (170000 to 190000 lbs per sq. inch). As the dies are sensitive to thermal stress, they should be warmed up slowly. Heating by oil or gas flames is to be avoided. The best method of heating the die is in an annealing furnace heated to the required working temperature of the die, the heating medium being either gas flames or preferably electric resistance heaters. In complicated dies, it may be necessary to provide air vents, as an unsatisfactory flow of metal in the forging is frequently to be traced to included air.

The compositions of some die steels are given in Table 31.

TABLE 31

## COMPOSITIONS OF STEELS FOR FORGING DIES

Light work	Heavy work	Heavy work & long runs
0.3% C 0.7% Cr 1.5% Ni	0.5—0.6% C 0.5—1.0% Cr 1.5—3.5% Ni about 0.4% Mo	0.3% C 2.0% Cr 8.0% W (0.3% V)

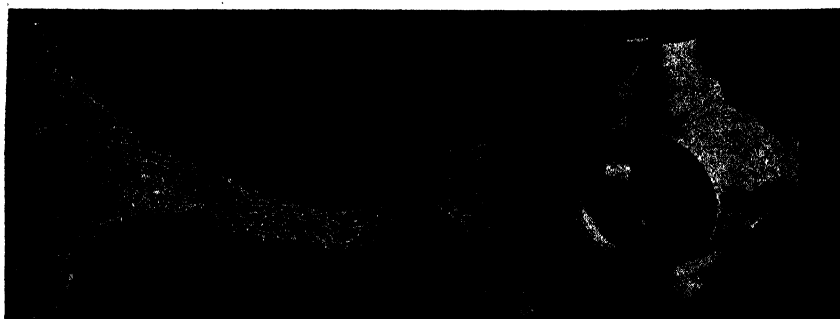


Fig. 246. Fibre structure in a wheel forging.

Fig. 247. Four-bladed propeller hub forging (Escher-Wyss) — cf. Fig. 248.

#### 4. SHAPING OF FORGINGS

To obtain the best mechanical properties in forgings, it is of great importance that the fibre structure should be correct. In particular the fibres should as far as possible run parallel to the direction of principal stress, and in highly stressed parts should always run parallel to the surface, as in the web of the railway waggon wheel illustrated in Fig. 246. In complicated pieces it is advisable in many cases that before the making of expensive dies, the course of the fibres should be investigated by small scale tests, as were done in the case of the dies for a four-bladed propeller hub, as shown in Fig. 248. In these trials, which were done on one-third scale models, the stock was represented by Plasticine and the dies were made of a cheap secondary aluminium.

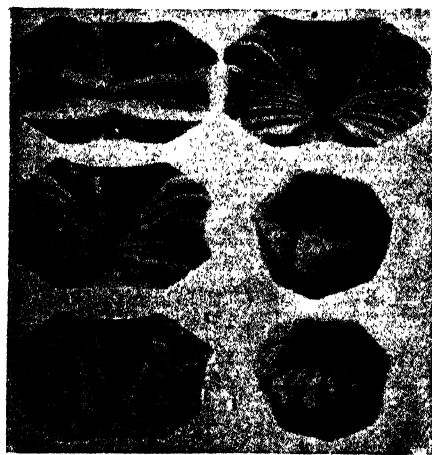


Fig. 248. Determination of fibre structure with Plasticine models.

A confirmatory test using the same cheap dies, but using high purity aluminium for the stock was also readily carried out and confirmed that the development of the fibre structure was the same as had been produced in the Plasticine test. The finished forging of the propeller hub by Escher-Wyss in Avional (Duralumin) is shown in Fig. 247. In extruded or rolled forging bar, the fibres of course always run parallel to the axis of the bar, and before drop forging, it is often necessary to give a preliminary rough forging or upsetting to bring about the required fibre arrangement. Thus Fig. 249 shows the forging operations

in the production of a motor piston. The billets cast by the continuous casting process are extruded to rod in the first place. Forging billets cut from the bar stock are upset, which causes the vertical fibres to become disposed horizontally for the greater part, and the "use" or dummy part-forged in this way goes then to the drop forging dies, in which it is placed on end. The operations in the forging of the propeller-blade, as shown in Fig. 250, are similar. Here the extruded bar is first rolled at right-angles to the direction of extrusion and then is drawn out under a hammer and finally finished in the dies. Fig. 251 shows the finished propeller-blade forging in the dies.

In the forging of light alloys, owing to surface oxide film, any cracks that may occur do not weld up in further forging as they may do in heavy metals. Should any cracks develop, they should be gouged out before forging is continued. The finished forgings are submitted to a careful examination for cracks, for which they are first cleaned in a bath. For this, a caustic dip is not advisable, especially in the case of the Al-Cu-Mg alloys, since it causes deep etching of grain boundaries. A bath composed of 4 parts 10% sulphuric acid and one part of concentrated hydrofluoric

acid is preferable, the pieces being given 3 minutes immersion. In copper-bearing alloys, the black colour which comes up must be removed by a subsequent 10 second dip in 40% nitric acid. After these dips, any cracks which may exist are easily seen.

## 5. DESIGN OF DROP FORGINGS

The principles of design are similar to those of die-

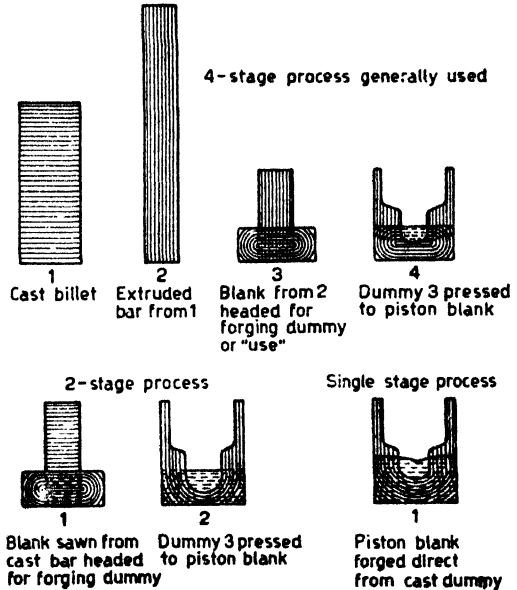


Fig. 249.

Stages in press-forging a piston (after Meyer).

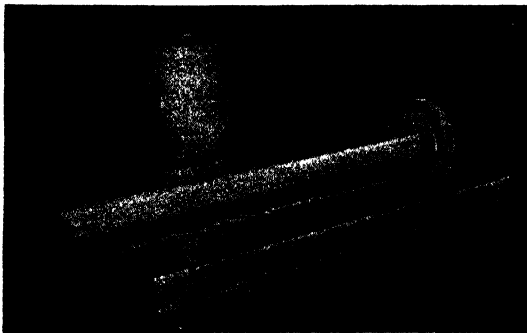


Fig. 250. Stages in the production of a propeller; cast billet, extruded bar, same cross-rolled.





Fig. 251. Finish forging of propeller under drop hammer (Alcoa).

castings. The simpler the shape of the piece, the cheaper is the making of the die, as well as the production of the forging. The machine designer should therefore not bring his design to finality without consulting the drop forging manufacturer. Sharp corners, excessive changes of section, and the inclusion of isolated thick places should be avoided. Owing to the relatively low malleability of the strong light alloys, the surfaces of the piece should be given an adequate draft in the direction of forging, as in Fig. 252. The minimum permissible thickness of the forging depends on its size. As

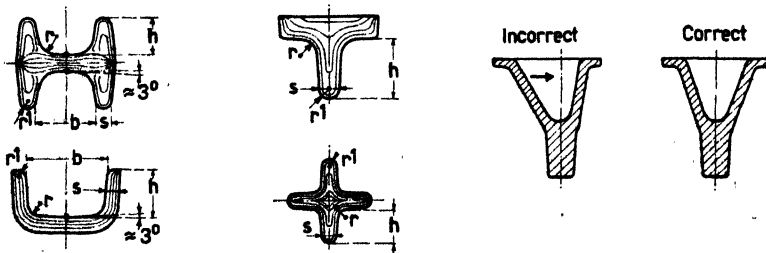


Fig. 252. Design of drop forgings.

far as possible, deep narrow ribs are to be avoided as it would require a high pressure to fill these, which would cause increased wear on the dies. The location of the flash and gutter is very important. As has already been seen in Fig. 244, the metal which flows out in the flash may cause a sucking effect on the forging and also influences the course of the fibre. Table 32 gives some general dimensional particulars applicable to drop forgings. Generally speaking the mechanical properties tend to be lower in the region of the flash, so this should be arranged in the region of lowest stress. Deep flanges and a central flash impart an unfavourable flow structure to H sections. T, U and cruciform sections are more favourable both in respect of ease of production and fibre structure. With H sections, large radii in the corners equal to at least half the depth of the flanges are essential, while in the other sections, the radii need be only half as much. Unsymmetrical pieces which tend to cant the dies should preferably be replaced by symmetrical pieces.

TABLE 32

DIMENSIONAL PARTICULARS FOR ALUMINIUM ALLOY DROP FORGINGS

Draft	Depth up to $1\frac{1}{2}$ "		Depth over $1\frac{1}{2}$ "	
	Slope	Angle	Slope	Angle
External surfaces . . . . .	1 in 20	3°	1 in 10	6°
Internal surfaces . . . . .	1 in 10	6°	1 in 6	10°

Wall thickness	Web and flange				
Surface area of forging, sq. inches	4 to 8	12 to 16	25 to 40	40 to 80	140 to 200
Minimum Wall thickness inches . . . . .	1/10	5/32	1/5	1/4	5/16

Ribs and flanges						
Min. thickness inch . . . . .	1/10	1/8	5/32	1/5	1/4	3/8
Max. depth, inch . . . . .	1/5	5/16	1/2	1	1 1/4	2

Converted from data sheet No. 17 of the Aluminium-Zentrale, Berlin, 1940.

## 6. FORGING OF MAGNESIUM ALLOYS

Magnesium forgings find application in certain cases, especially in aircraft construction. The forging of magnesium alloys is a more difficult matter than that of aluminium alloys owing to the hexagonal crystal structure. It is important that the forging temperature should not exceed 470°C (878°F) in the case of the Mg-Mn alloys, nor 420°C (788°F) for the Mg-Al alloys, while on the other hand forging must not be carried on below



Fig. 253. Impact extruded articles (Volt, Tilburg).

300°C (572°F). Figs. 185 to 187 show the pressure required for forging some magnesium alloys. The most easily forged alloy is the 2%Mn alloy, which has the lowest strength. For forgings of maximum strength, the alloy with 6% Al is used in Europe, and with 8.5% Al in America. The design and construction of the dies follow the same lines as for aluminium, although a somewhat greater degree of draft is an advantage, while gradual changes of section, where such exist, and large radii at channels or ribs are very necessary. Forgings in magnesium alloys require a greater forging pressure than in aluminium alloys. Thus with a 16 ton drop hammer, forgings can be produced up to 30 by 30 inches in size and 100 pounds in weight, while a 2500 ton forging press will handle pieces up to 14 by 14 inches and 26 pounds in weight. In general, pressing is to be preferred to striking under the drop hammer, as a shape with less draft or obliquity of the edges can be produced by the former method. The mechanical properties of drop forgings in an alloy containing 8.5% Al, 0.5% Zn, 0.2% Mn after heat-treatment are: tensile strength 21 tons/sq. in. (47000 lb./sq. in.), proof stress 15 tons/sq. in. (34000 lb./sq. in.), elongation 6%, which compare with the Al-Cu-Mg forging alloy of 27 tons/sq. in. (60000 lb./sq. in.) tensile strength, 18 tons/sq. in. (40000 lb./sq. in.) proof stress and 10% elongation.



Fig. 254. Impact extrusion machine (von Roll).

## 7. IMPACT EXTRUSION

Impact extrusion is a method of fabrication mainly used for pure aluminium, but latterly alloys also have been processed by this method. With pure aluminium, the impact extrusion process is carried out at room temperature. The process was first used for the mass production of collapsible tubes in tin. Owing to the high price of tin, the industry turned over later to the production of pure aluminium collapsible tubes, while today a large range of parts used in the construction of wireless and other apparatus, such as are shown in Fig. 253, are now made by this process in aluminium. A press for impact extrusion is shown in Fig. 254, the process tools, i.e., dies and punches, being shown in Fig. 255. To carry out the pro-

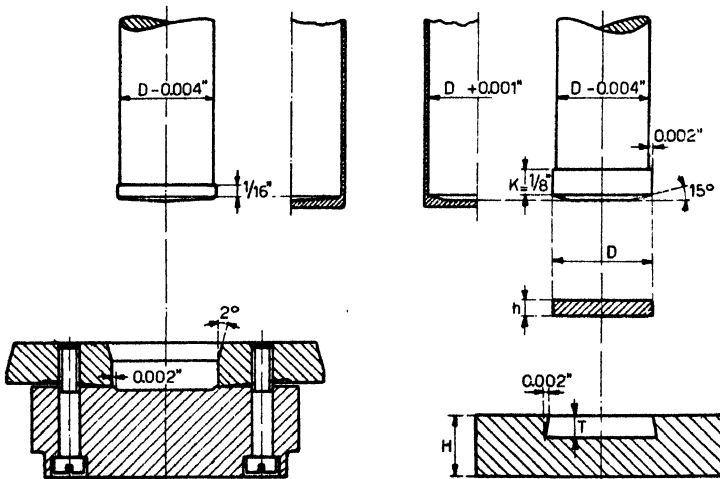


Fig. 255. Impact extrusion press tools.

cess, a slug, punched from plate or parted from round rod, is placed in the die, and under the percussive pressure developed between the sharp edged face of the punch and the die at the bottom of the working stroke, is extruded instantaneously upwards, a pressure of about 110 tons/sq. in. (250000 lb./sq. in.), or more being required. Alloy slugs are usually preheated to 200° to 300°C (392° to 572°F) and the press tools must be brought to a similar temperature. In comparison with deep drawing from sheet blanks, described in a subsequent chapter, production by impact extrusion has the advantage when the depth of the article is more than  $1\frac{1}{2}$  times the diameter, especially for thin cylinders only a few thousandths of an inch thick. A fully automatic impact extrusion press will produce several thousand pieces an hour and with pure aluminium the punch will stand up for 200000 pieces, while the die ring lasts longer. The dimensional tolerances on impact extruded articles are shown in Table 33.

TABLE 33

## WORKING TOLERANCES FOR IMPACT EXTRUDED ALUMINIUM TUBES

Tolerance-inch.	Tolerance-inch.
Wall thickness $\pm (.001 \times .05 t)$ ( $t$ = wall thickness)	Outside diameter $\pm .002$
Thickness of base $\pm .004$	Inside diameter $\pm .001$

## CHAPTER X: DRAWING OF TUBES AND SECTIONS

### 1. GENERAL

In extrusion there is a minimum limit to the wall thickness, which depends on the alloy and the section, and in general lies about  $1/16$  inch for pure aluminium and  $1/8$  inch for those alloys that are difficult to extrude. If

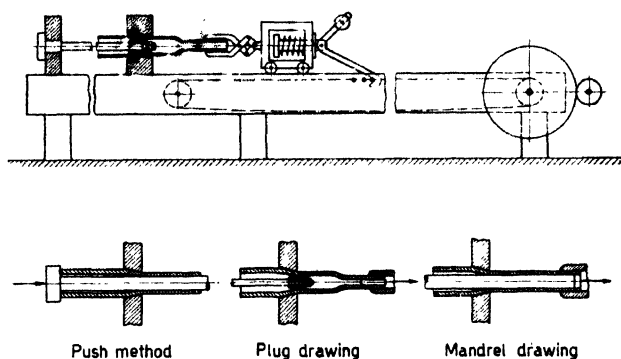


Fig. 256. Tube drawing.

thinner walled sections are required, they are reduced by a subsequent process of cold drawing. The tube drawing factory is of considerable importance, as there is a steady demand for tubes down to .020 inch wall

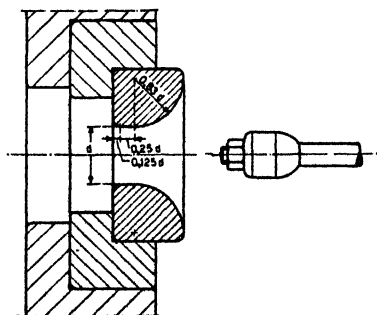


Fig. 257. Tube drawing tools.

\* or bulb (U.S.A.)

thickness. The reduction of the wall thickness of tubes is brought about by drawing them between a die and a mandrel or plug, as shown in Fig. 256. There are two methods of drawing; mandrel drawing in which a substantially parallel mandrel is used to size the bore, and plug drawing in which a short plug\* held at the end of a thinner plug rod sizes the bore. In the case of thick tubes, instead of drawing the tube and mandrel through the die, these may be pushed through the die on a "push

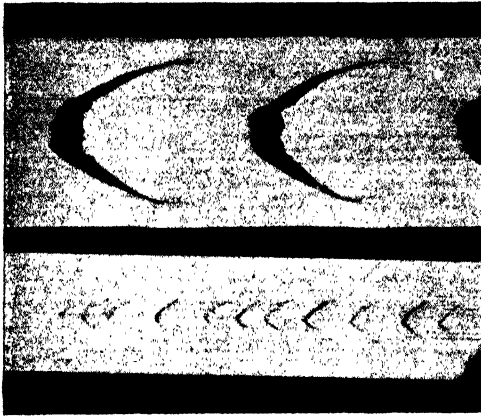


Fig. 258. Cupping defect in drawn rod.

The die is trumpet shaped or conical with an included angle of 4 to 6° for tube drawing or 3.5 to 4° for rods, although it is common practice to use tube dies for drawing rods also. As the drawing process is carried out cold, the die steels used are different from those used for extrusion dies. Table 34 shows the composition of steels used for dies and plugs. These are hardened to a Brinell hardness of 500 to 550 and highly polished. The best lubricant for tube drawing consists of 60% beeswax, 30% tallow and 10% cylinder oil. Cheaper lubricants that may be used are lanoline, machine oil and rape oil. Before re-use, the lubricant must be thoroughly filtered to extract all suspended particles. Lubricants

bench". Tube drawing is carried out on a draw bench, which comprises a die plate, against which the die bears in drawing, a back extension with a bracket for holding the back end of the plug rod, which must be capable of adjustment in order that the plug may be accurately registered with the die, and a drawing dog or pliers, by which the tube is pulled through the die. Fig. 257 shows the die plate with a die in position for drawing, together with the corresponding plug.

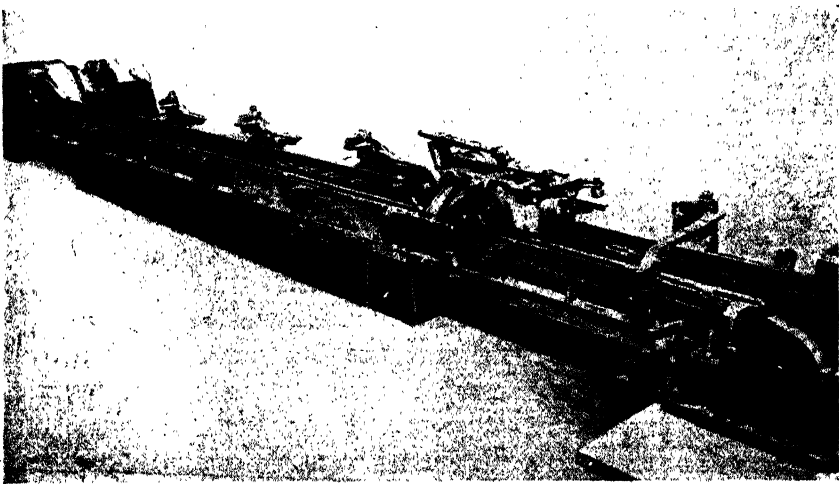


Fig. 259. Drawbench (Wellman).



Fig. 260.

Tube works (Reynolds Tube Co. Ltd., Birmingham).

that have been in use for the drawing of heavy metals must on no account be used for the light metals, and the lubricants should be changed between copper-containing and copper-free light alloys. In cold drawing, the material hardens up more rapidly than in cold rolling, so that annealing is required after a smaller percentage reduction in drawing than in rolling. The economical

total reductions of area between anneals are for Al-Cu-Mg alloys 20 to 30%; for Al-Si-Mg alloys about 50%, and for pure aluminium about 75%. The draft, or reduction of area per pass, varies between 15 to 25% according to the alloy.

TABLE 34

COMPOSITIONS OF STEEL FOR DRAWBENCH DIES AND PLUGS %

C . . . . .	0.25	0.2	1.1
Si . . . . .	—	—	0.3
Mn . . . . .	0.3	0.3	0.3
Cr . . . . .	1.5	1.5	0.6
V . . . . .	—	—	0.25
Mo . . . . .	1.5	1.5	—
Ni . . . . .	1.5	1.5	—
W . . . . .	1	3	—

The draft should be as heavy as possible in order to ensure uniformity of deformation throughout the section. With light drafts, only the surface is deformed and internal fissures may be formed, as in Fig. 258. For annealing, if a lubricant that volatilises without residue is not used, the tubes must be degreased before being annealed. For this purpose a trichloroethylene degreasing tank can be conveniently used. To permit the entry of the tubes into the dies, they must be pointed or tagged. This can be done on pointing rolls, swaging hammers, rotary swaging machines, or by sawing down and hammering close. Fig. 259 shows a tube drawbench, and Fig. 260 a tube factory.

The cold drawing of sections is a much more difficult matter than that of tubes. With different wall thicknesses the same percentage reduction



must be taken in order that stresses causing distortion are not created in the section. Sections for drawing are best pointed by grinding or milling. Section drawing is carried out to a lesser extent than tube drawing, and the loss of strength in finally heat-treated materials, as explained on p. 204, must be taken into consideration.

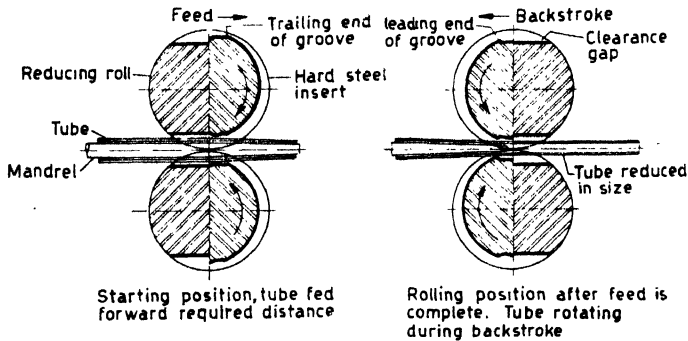


Fig. 261. Tube rolling machine — (Tube Reducing Corp.).

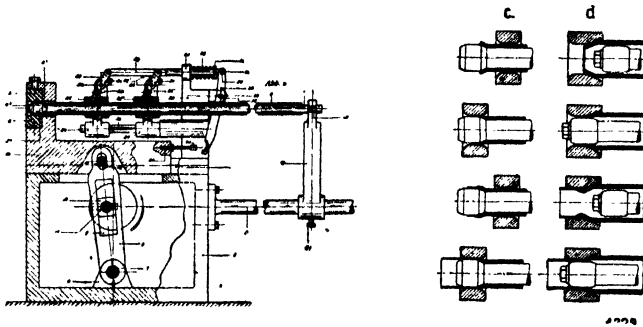


Fig. 262. Singer reciprocating tube machine.

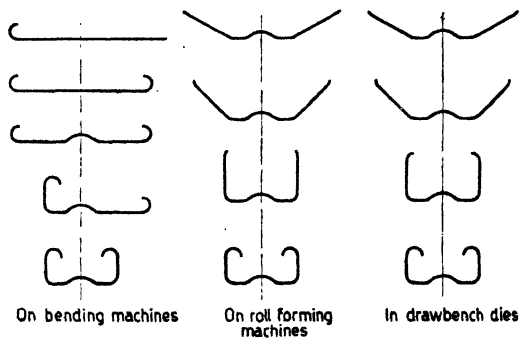


Fig. 263. Forming of sections from strip stock.

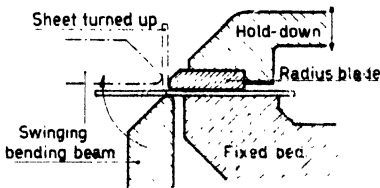
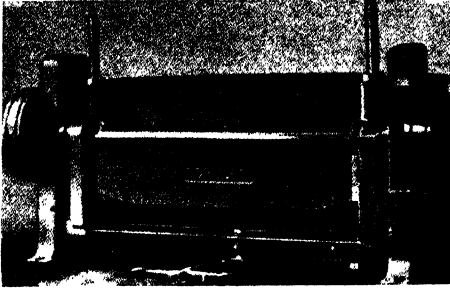


Fig. 264. Universal sheet folding machine (Schuler).

The Singer tube machine shown in Fig. 262 employs a different method of working. In this the tube is pushed forward over a plug, and a drawing die then draws down the projected portion of the tube over the plug. After retraction of the die, the tube is advanced a further distance over the plug and again the forward movement of the die compresses the tube on to the plug. In another method of working the tube is pushed into the die and is then reduced by the advancing of the plug. In both machines, much bigger reductions without annealing can be effected than on the drawbench, for example the wall can be reduced from .120 inch to .040 inch in Avional or Duralumin tubes.

## 2. TUBE REDUCING MACHINES

Tube reducing machines are being used to an increasing extent instead of the conventional drawbenches for the production of tubes. The prototype was introduced by the Tube Reducing Corporation (U.S.A.). The principle of operation is shown diagrammatically in Fig. 261. A pair of rolls reversing automatically at  $180^\circ$  with tapered reducing grooves, similar to pointing rolls, compresses the tube on to a tapered mandrel. When the rolls turn backwards, the tube is freed, rotated through  $30^\circ$ , and pushed forward a short distance over the mandrel, when it is again engaged by the rolls and further reduced.

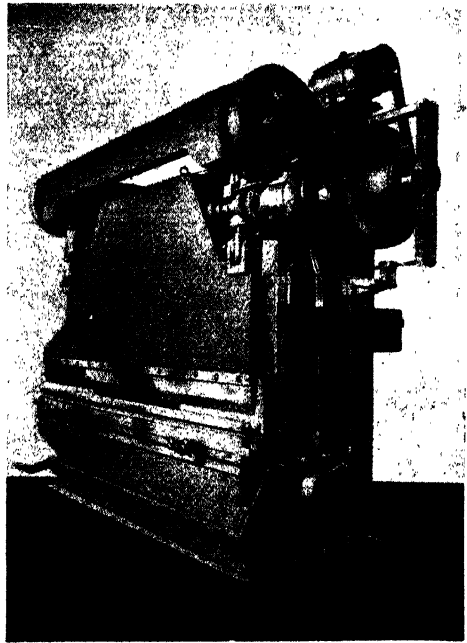


Fig. 265. Press brake (Nobs & Co., Thun).

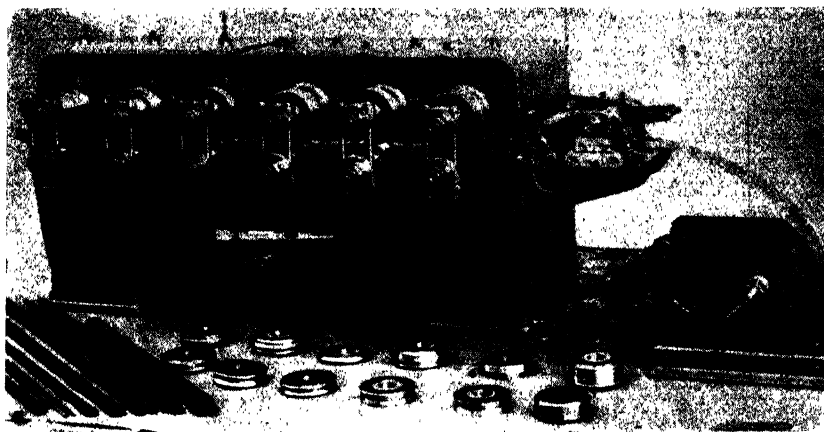


Fig. 266. Roll forming machine for forming sections from strip stock (Weingarten).

### 3. FORMING OF SECTIONS FROM STRIP

Thin walled sections, such as are much used in aircraft construction, may be formed from strips. As shown in Fig. 263, this may be done by bending, rolling or drawing. Bending may be done on folding machines, as shown in Fig. 264, one bend being made in one operation. Another type of machine is the press brake, Fig. 265, which is like a shear, but set parallel, the descending beam forming a bend in the strip stock. In contrast to these machines, in rolling and drawing all bends are usually formed in one operation, which may embody a series of steps to give the shape required. In bending machines the time of manipulation is excessive and for long lengths very big machines are needed, but in rolling and drawing machines for forming sections the process is continuous. Roll-forming is shown in Fig. 266. In drawing sections from strip, forming is done by drawing the strip through a series of dies. While extruded sections can be produced with sharp corners, sections formed from strip must have radii of 1 to 3 times the sheet thickness according to the alloy. In general, such sections can be produced up to a thickness of .080 inch. For thicker sections, direct extrusion is the more economical method of production.

## CHAPTER XI: WIRE MANUFACTURE

### 1. GENERAL

The good electrical conductivity, corrosion resistance and tensile strength of aluminium and Aldrey (Al-0.5Mg-0.5Si), or Silmalec as it is known in Great Britain, render these materials suitable for use as electric conductors. In Fig. 267 and Table 35 are given a comparison of the relevant properties of various conductor materials. Starting with wire-rod or bolt produced by rolling or extrusion, the diameter of the wire is reduced by a process of wire-drawing carried out cold, using a die of a type somewhat similar to those used in tube drawing. The angle of the die is of great importance in wire drawing. For hard material this is  $10^\circ$  and for soft  $20^\circ$ . As the material hardens up in drawing, the wide angle dies are used in the opening drafts when the material is softer, and after about 5 drafts, the narrow angle dies can be substituted with advantage. Fig. 268 shows the correct profile for steel, hard metal carbide, and diamond dies. With pure aluminium and Silmalec, the drafts are somewhat lighter than with copper, giving about 20 to 25% reduction of area per draft.

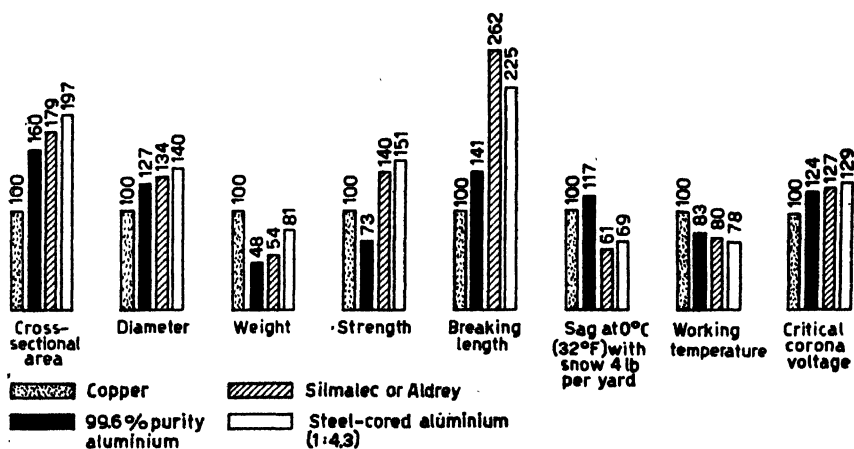


Fig. 267. Comparison of electric cables of equal resistance per mile (copper taken as 100).



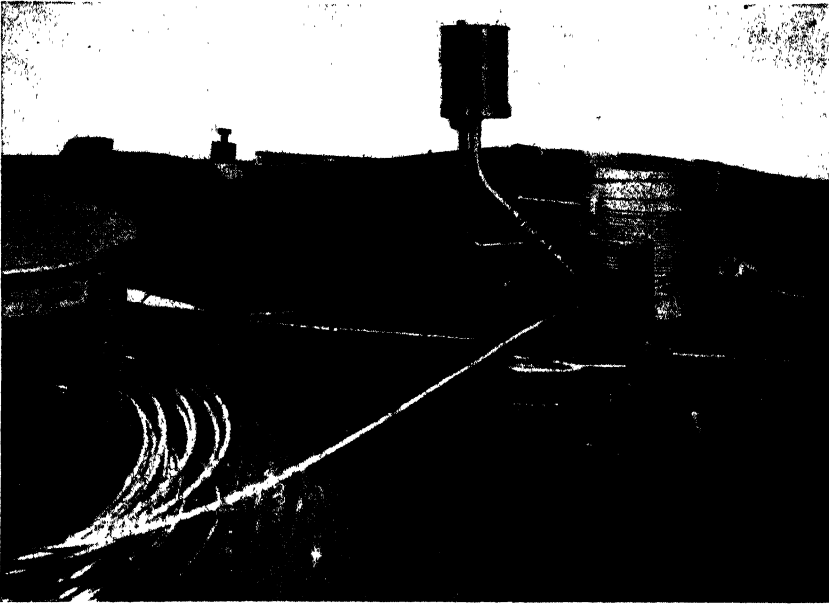


Fig. 269. Single wire block.

The drawing process starts on single wire blocks (Fig. 269), for which copious lubrication must be provided on the die, especially for the first draft. The best arrangement is to have a jet of oil playing on the wire running into the die. The excess of oil is collected below the wire block and runs through a sieve into the collecting tank. In the drawing dies, the important parts of the surfaces are the reducing cone proper, a short

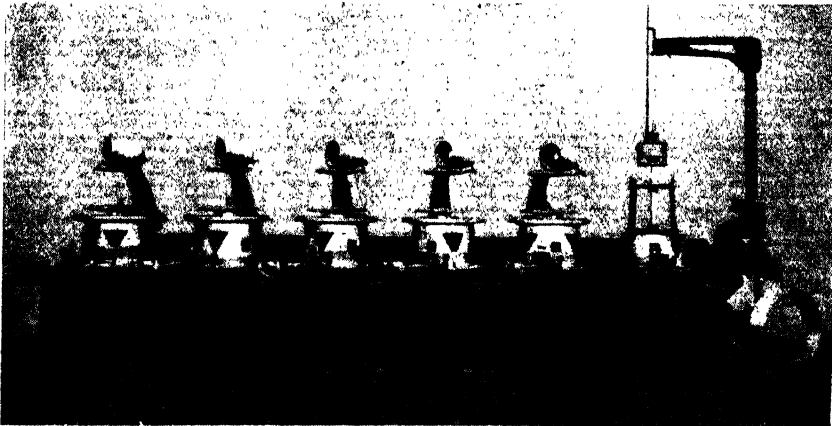


Fig. 270.

Special multiple block continuous wire-drawing machine for aluminium wire (Kratos).

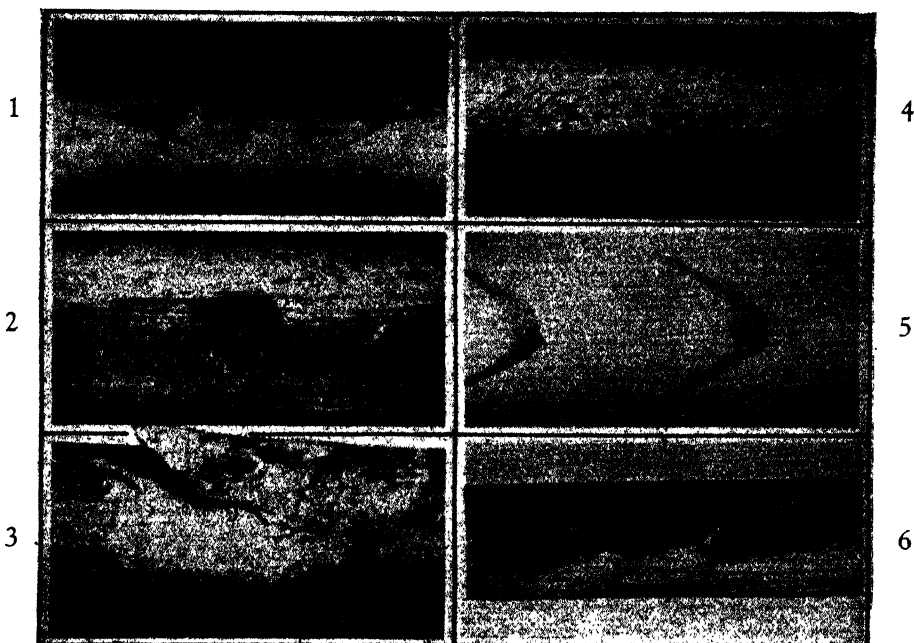


Fig. 271. Defects in wire :

1 Defect due to tearing of slivers in rolling.

2 Foreign metal rolled in.

3 and 4 Torn wire due to insufficient lubrication in drawing.

5 Cupped or internally fissured wire due to excessive draft.

6 Impression of harder steel core wire in aluminium wire in a steel cored aluminium cable that has been in service.

parallel bearing portion at the end of the cone, the leading bell-mouthed aperture and the backing, or short reverse cone at the outgoing side. The dimensions are given in the illustration. Below 0.280-0.320 inch, the wire is generally drawn to finished size on continuous wire-drawing machines with multiple dies, and with such machines it is essential to have good cooling arrangements for the lubricant, as if it gets hotter than 100°C (212°F) a "letting-down" or slight softening effect takes place on the metal, which reduces the tensile properties of the finished wire. Since aluminium is susceptible to surface damage, the multiple die machines as used for copper wire drawing, in which the wire slips on the drums, are not entirely satisfactory, and therefore wire-drawing machines, as in Fig. 270, are made specially for aluminium in which after each draft the wire runs round a drawing block and from round idle sheaves to the next die. The use of steel or chilled iron drawing dies in continuous multiple die machines is not satisfactory, and hard metal carbide dies and diamond dies are used. Such dies, with proper conditions of lubrication, are good for the drawing of many tons of .080 inch wire before they require repolishing. The finished wire must have a surface free from defects. Defects may originate right

back to the rolling process. In the wire drawing process, defects originate through incorrect die angles, incorrect conditions of lubrication, as well as slivers of metal rolled in (Fig. 271).

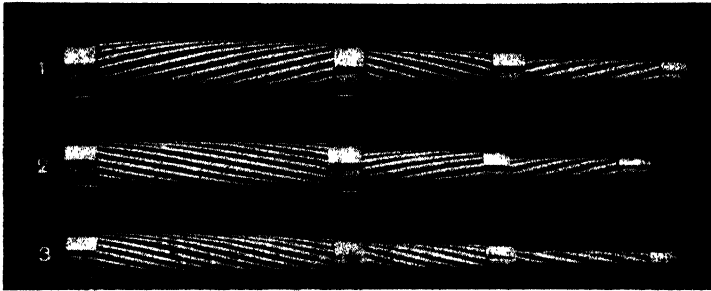


Fig. 272. Different methods of stranding.

- 1 Opposite direction of lay for all layers.
- 2 First and second layers same direction of lay, third layer opposite hand.
- 3 All layers same hand.

## 2. ALDREY, SILMALEC, ALMELEC<sup>1</sup>

A percentage cold reduction of at least 90% (of area), or better still 95%, is necessary to impart to wire of this alloy its high strength properties. With these reductions, the wire has a proof stress of 50000 lb./sq.in., a tensile strength of about 57000 lb./sq.in. and an electrical conductivity of 27 reciprocal ohms per sq. mm per metre or 46.5% International annealed copper standard. In this condition, the wire is too brittle and the conductivity too low. By letting down by heating for 8 hours at 150°C (302°F) the conductivity increases to 31.5 m/ohm. mm<sup>2</sup> or 54.1%, while the proof stress decreases to 41000 lb./sq. in. and the tensile strength to 46000 lb./sq. in., while the elongation increases to 8%. This heat-treatment results in a material which is extremely suitable for overhead conductors.

## 3. MANUFACTURE OF CABLES

The particular properties of aluminium need to be taken into consideration in the manufacture of cables, as in other products. To increase the strength, steel-cored aluminium cable is frequently used, having a thin steel core of 7 wires surrounded by 2 or more layers of aluminium wires. In the usual method of cross stranding, in which as shown in Fig. 272, each layer is laid with the opposite direction of twist from the layer underneath it, the softer aluminium wires are liable to be indented by the hard steel wires, as in Fig. 271, which tends to impair their breaking strength. This can be avoided by stranding the innermost layer of aluminium wires with the same lay as the steel wires. With all-aluminium and Silmalec

<sup>1</sup> (These names are synonyms for similar Al-0.5Mg-0.5Si alloys)



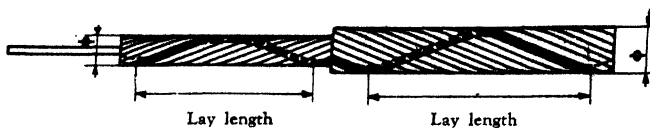


Fig. 273. Different lengths of lay in aluminium conductor.

(Aldrey) cables also, it is advisable to strand the first and second layers with the same lay to avoid marking due to the stranding stress, and only to strand the third layer with the opposite lay. The angle of lay depends on the diameter of the cable and the lay (length of one complete twist divided by the outside diameter of the layer) is 10 to 15, the inner layers usually being stranded with a shorter lay than the outer (Fig. 273). The notch-sensitivity of aluminium requires that damage to the surface of the wire shall be completely avoided at all stages of cable manufacture. This requires special care on the stranding machines in which the wire can very easily be damaged.

As the corona loss in high-tension cables increases inversely as the diameter of the cable, aluminium conductors have an advantage over copper in a lower corona loss at high voltages, owing to the greater diameter of aluminium for equivalent conductivity. In extra high tension work, however, even the light metal cables must be increased in diameter by the use of a hollow construction (Fig. 274). In this illustration is shown, on the extreme left, a hollow anti-vibration Aldrey conductor. In the hollow space in this cable, there is a thin steel cable of smaller diameter than the hollow space, which owing to its different natural frequency of vibration renders it impossible for resonant vibrations to be developed in the composite cable. The steel core also serves to impart increased strength to the whole cable.

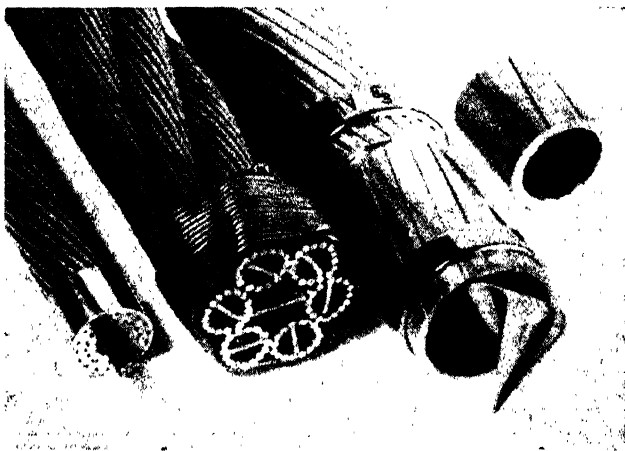


Fig. 274. Left, vibration-free cable, rest hollow cable construction for Aldrey (Silmalec).

## CHAPTER XII: SPINNING AND PRESS-WORK

### 1. METAL SPINNING

For the production of round hollow articles, the process of metal spinning is used where the number required is small, while for large quantities, according to the shape, the deep-drawing (or pressing) process, or a combination of the pressing and spinning processes are used. Spinning is essentially a manual process requiring much skill on the part of the operator. Pressing is a purely mechanical process, and one which requires expensive machines and press tools.

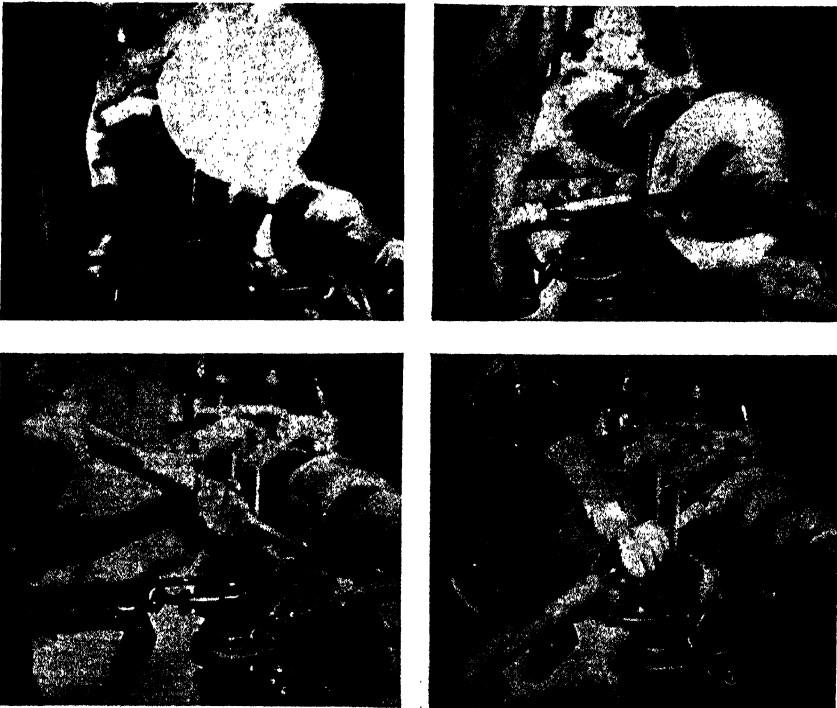


Fig. 275. Procedure in metal spinning.

Upper left: Chucking of blank.

Lower left: Final spinning and planishing.

Upper right: Commencement of spinning.

Lower right: Trimming the edge.



Fig. 276. Large spinning lathe (Aluminium Welding Works Ltd., Schlieren, Switzerland).

of 1500 to 3000 feet per minute according to its diameter, thickness and hardness, the slower speeds being used for thicker circles and harder metal. When the spinning lathe has been brought up to the correct speed, the circle is pressed on to the chuck in a series of steps by the pressure of a

Metal spinning is carried out on a simple spinning lathe, as shown in Fig. 275. The sheet metal circle or blank which is to be spun into the hollow article is clamped by the ball-bearing backwood or tailstock pad against the spinning chuck, which is mounted on the headstock spindle. Before commencing to spin the blank, the operator must centre it accurately while turning it slowly. Then he lubricates it, using for small thin circles beeswax, tallow or lard oil, preferably mixed with petroleum jelly. For large heavy spinnings, soap is preferable. The circle is rotated at a peripheral speed

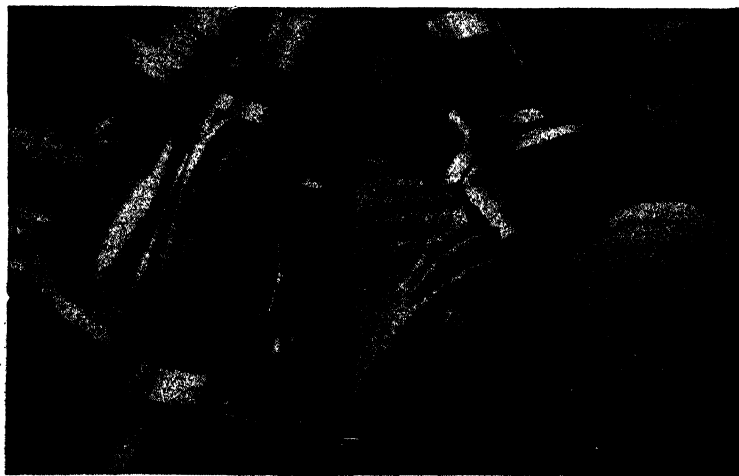


Fig. 277. Chucks for necked vessels (Alcoa).

spinning tool, as shown in Fig. 275. In this operation, the back pressure of the spinning tool is taken against a peg inserted in a convenient one of a series of holes in the hand rest, which gives a big leverage. To increase his purchase in heavy work, the operator will attach himself to his lathe by means of a strap passed round his body.

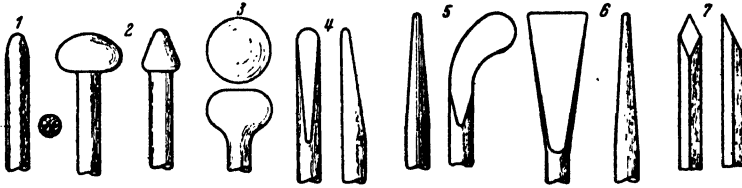


Fig. 278. Tools for metal spinning.

- |                                 |                                    |
|---------------------------------|------------------------------------|
| 1 Round-nosed (point and ball). | 5 Groover.                         |
| 2 Raising-up tool.              | 6 Planisher (fish-tail).           |
| 3 Knob raiser.                  | Trimmer (diamond point or graver). |
| 4 Turning-over tool.            |                                    |

The chuck, in the case of small quantity jobs, is made of boxwood, pine or maple wood. Such a chuck may, if desired, be protected against excessive pressure in use by sheathing with a spun-on sheet circle. For large quantity jobs, metal chucks are used, and these, as shown in Fig. 277, may, when the shape requires it, be of sectional construction like a gravity die-casting core in order that a spun vessel with a constricted neck may be removed from it.

Fig. 278 shows a range of metal spinning tools. Very skilled operators

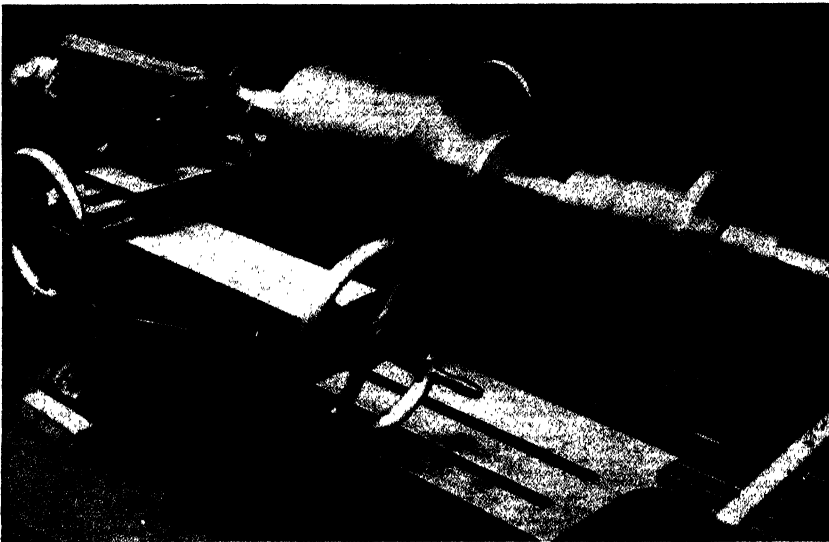


Fig. 279. Heavy spinning lathe with roller tool on slide rest.

can spin "on air" without a formed chuck, using merely a hard-wood stick to hold up the spinning under the tool. Also in spinning down large circles, until they lie along the chuck, a hard-wood stick is used when necessary to hold the metal up against the tool. For the spinning of circles

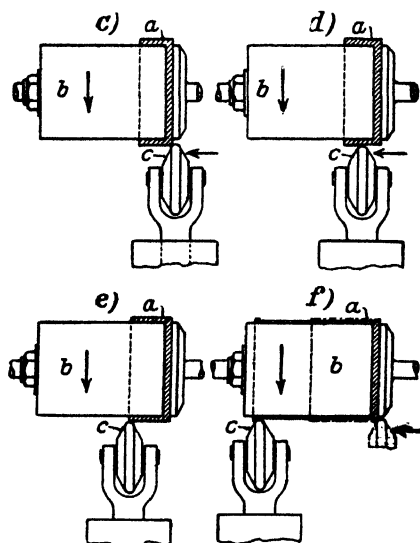


Fig. 280.

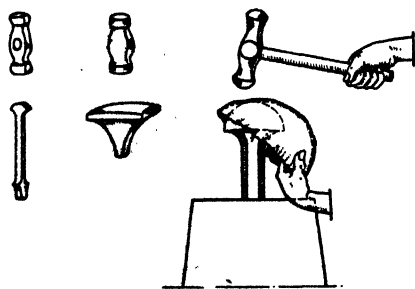
Spinning of cast pans (Kuhn process).

of larger size and of heavier gauges, especially in alloy, instead of a hand tool, a roller tool mounted on a slide rest is used, as in Figs. 276 and 279, and the spinning is sometimes carried out hot, the metal being heated to  $250^{\circ}$  to  $300^{\circ}\text{C}$  ( $482^{\circ}$  to  $572^{\circ}\text{F}$ ) by means of a gas flame. Higher temperatures are not used owing to destruction of the lubricant. The force required for spinning different materials varies in similar manner to rolling, extrusion and forging, that is to say that pure aluminium and Al-Mn alloy require the least force, and Peraluman 5 (Al-5Mg) and Avional or Duralumin (Al-Cu-Mg) require the greatest.

In some cases, round hollow articles are produced by firstly drawing straight-sided shells on a draw-press, and finally spinning them to shape on a lathe; or the side wall of a cast pot can be drawn out longer and thinner by spinning, as in Fig. 280, the base remaining unchanged. Cooking utensils for electric hot-plate stoves are produced in this way, as the thick base does not become distorted but remains flat, thus ensuring a high efficiency of heat conduction. In metal spinning it is possible to make the walls of the vessel thinner or even thicker at any desired place than the blank from which the spinning is made.

## 2. BEATING

The art of beating is used to some extent in forming aluminium sheet, in the manner of copper-smithing. The metal is beaten over a hardwood



block of shape suitable to the conformation of the article, or over a leather sand bag, a beating hammer as

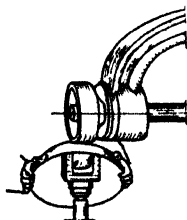


Fig. 281. Tools for beating and wheeling.

shown in Fig. 281 being used. For some hammered work, specially shaped anvils are used. A variation of the process is wheeling or rolling, in which the sheet is rolled between convex and concave rollers turned by hand or power. As in spinning, beating is essentially hand work, but is capable of giving a wide variety of shapes without the use of costly equipment.

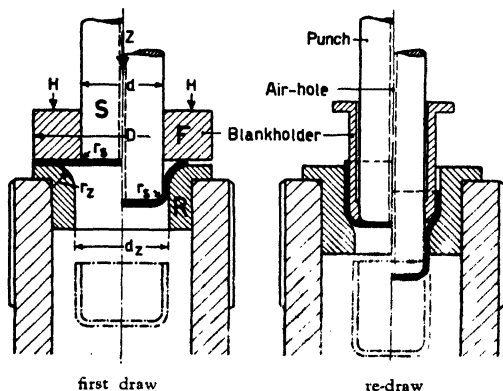


Fig. 282. Deep drawing — schematic.

### 3. PRESSING

In contrast to spinning and beating which are manual processes calling for a considerable degree of dexterity, the production of hollow particles by pressing or deep drawing is a purely mechanical process. A flat blank of suitable shape and size is placed between the die R (Fig. 282) and the

pressure ring or blank holder F and is drawn through the die by the downward motion of the punch S. In the drawing operation, the part of the blank lying between the blank holder and the die slides between the surfaces of these and through the narrow clearance space between the punch and the die, forming itself into a shell fitting closely around the punch. Owing to the contraction of the periphery of the blank, a thickening-up of the metal takes place, which may increase the thickness to as much as 1.4 times the original thickness of the blank. For this reason the clearance between the punch and die must always be greater than the original sheet thickness, otherwise the metal will jam between them, the friction will become excessive and the base of the pressing will be torn out by the punch. If thin sheet blanks are drawn without a blank holder, the contraction of the periphery as the operation proceeds causes wrinkles to form in it which also become jammed in the clearance space between the punch and die. The tendency

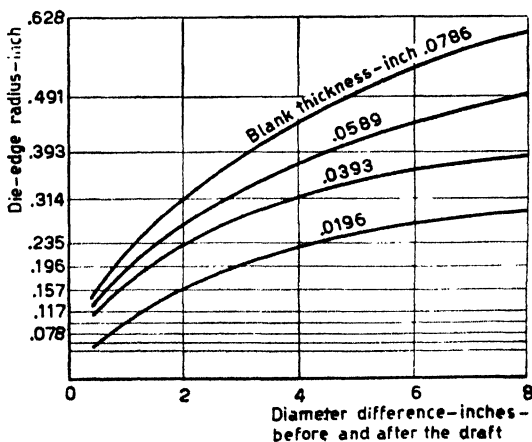


Fig. 283. Relation of die-edge radius to blank thickness and diameter difference (draw-ratio).

to wrinkle is reduced by increasing the radius on the edge of the die. For aluminium, the size of the die-edge radius varies up to  $5/8$  inch, depending on the thickness of the stock and the difference in the diameters of the blank and the drawn shell, as shown in Fig. 283, where this difference is termed "diameter difference". Furthermore the ratio of the punch diameter to the thickness of the stock has an effect on the formation of wrinkles. If this is smaller than 50, as with a 4 inch punch and an .081 inch gauge blank or thicker, it is possible by the use of a correct die-edge radius to draw a shell without the use of a blank holder.

The relative depth of draw, or expressed in another way, the draw ratio, is a factor of great importance for economical operation. The draw ratio for the first draw is the ratio of the punch diameter to the blank diameter, and for re-draws is the ratio of punch diameter to shell diameter before the re-draw. Table 36 gives the draw ratios for various materials.

TABLE 36  
DRAW RATIOS IN DEEP DRAWING

	First draw	Redraws
Brass . . . . .	0.50	0.8
Deep drawing steel sheet . . . . .	0.55	0.8
Aluminium . . . . .	0.55	0.8
Al-Cu-Mg alloy (Duralumin) . . . . .	0.60	0.9
Zinc . . . . .	0.65	0.9
Magnesium . . . . .	0.65	0.9

The blank holder pressure required depends on the draw ratio, the die-edge radius, and the nature of the stock and is proportional to the

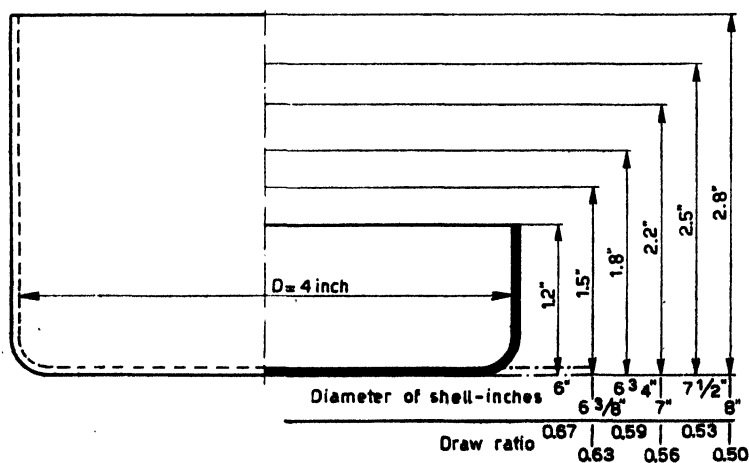


Fig. 284. Draw ratios and depth of draw for first draw.

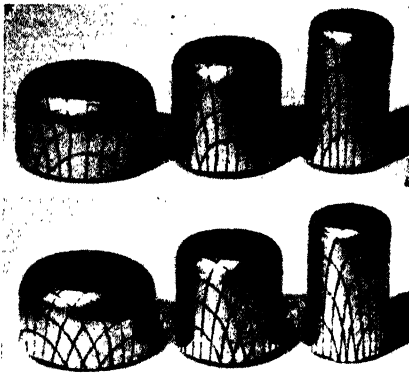


Fig. 285.  
Lines of flow in 3 drawing operations.

thrust or load required for drawing. The blank holder load is 10% of the drawing load for Al-Cu-Mg alloys (Duralumin), 17% for the Al-Mg alloys, and 20% for pure aluminium and the 1½% manganese alloy. This is equivalent to a blank holder pressure of 90 to 140 lb./sq. in. It is important that this pressure is uniform over the entire surface of the blank holder, which calls for a uniform thickness in the blank, and remains constant as the draw proceeds. The latest practice is to use a compressed air loading for the blank holder which gives the most exact conditions.

The drawing load can be computed from the following formula:

$$T = \pi \cdot d \cdot t \cdot n \cdot f_t$$

where  $T$  = the drawing load in tons

$d$  = diameter of the punch in inches

$t$  = thickness of stock in inches

$n$  = a factor dependent on the draw ratio (see below)

$f_t$  = the tensile strength of the stock in tons/sq. in.

$T$  and  $f_t$  can both be in lb. units if preferred.

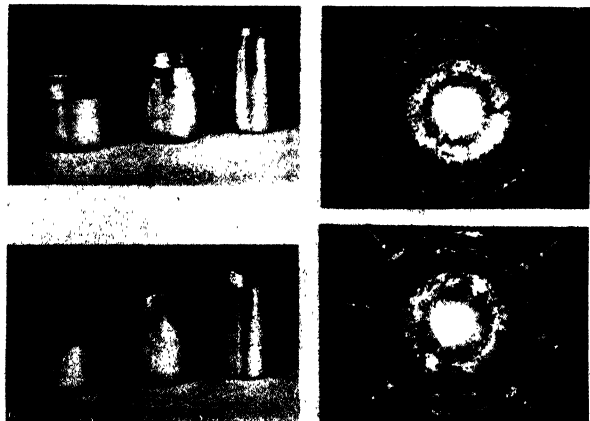
The value of the factor  $n$  varies with different draw ratios  $\frac{d}{D}$  (Fig. 282) as under:

Draw ratio $\frac{d}{D}$	0.55	0.6	0.65	0.7	0.75	0.8
Factor $n$	1.0	0.86	0.72	0.6	0.5	0.4

$D$  = initial diameter of blank.

When drawing is done with a sequence of re-draws, the shape of blank holder and punch for the redrawing operations are as shown in Fig. 282 right. Fig. 284 shows the relationship between draw ratio and relative depth of draw.

Fig. 286. X-ray patterns and ear formation in drawing of pure aluminium.





Practical tests have shown that with a 100 ton press, pure aluminium circles up to 12 inches diameter and .080 inch thick can be drawn to 7 inch diameter shells; with a 300 ton press 28 inch diameter circles 1/8 inch thick can be drawn to 17 inch diameter shells. The manner of deform-

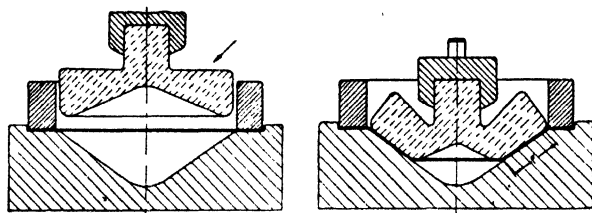


Fig. 287. Drawing with a rubber punch.

ation of circular blanks can be seen in Fig. 285, where a network of lines at right angles was drawn on a circle before drawing. The progressive compression of the peripheral zone at each successive draw is clearly visible. The structure of the material affects the drawing result. If the structure has a directional character, the formation of points or "ears", which can be seen in Fig. 286, will result, which are not formed with material free from directionality as shown by X-rays. According to the axis of directionality the ears come at 0 and 90° to the direction of rolling, or at 45° and 45°. The former direction occurs if the (100) planes and (100) edges lie in the direction of rolling. It is thus evident that the prior rolling processes have a pronounced effect on the behaviour of the material in deep drawing.

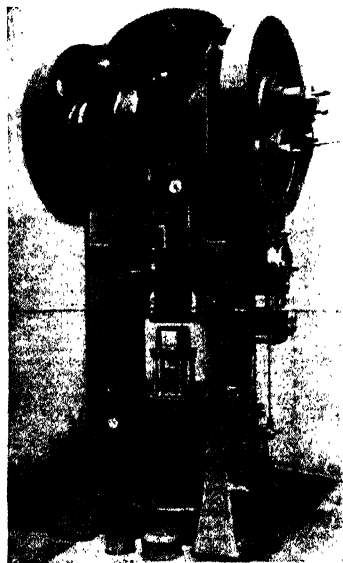


Fig. 288. Crank press  
(Maschinenfabrik Weingarten).

It is possible to produce not only cylindrical shells but bowl shaped and conical shells also by the deep drawing process, as well as other shapes. For such work the blank holder pressure must be so high that the blank is not drawn through the die. Instead of a metal punch, a rubber punch as can be seen in Fig. 287, is often used. The die for deep drawing is always made of hardened steel, sometimes chromium plated, but for light draws, cast iron, cast zinc, or hard wood may be used, the last named requiring protection from moisture. To reduce the drawing load, small articles are lubricated with a mixture of molten tallow and paraffin in equal proportions, while for large articles

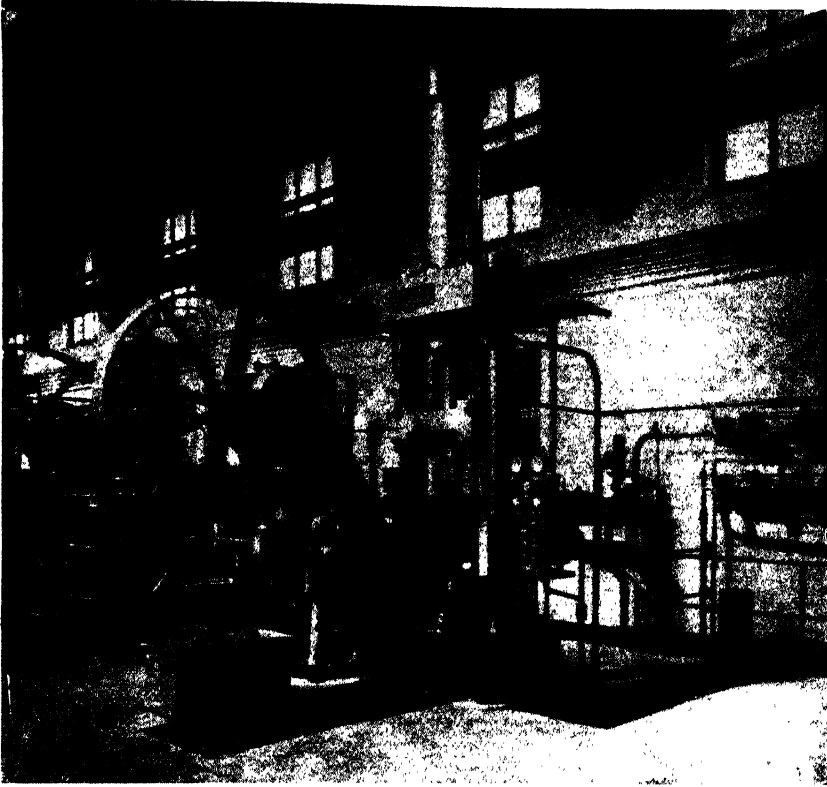


Fig. 289. Hydraulic draw-press (Sulzer Bros).



the proportion is 1 to 2, or a petroleum-jelly/graphite mixture is also good.

Regarding the type of press used, crank presses, as illustrated in Fig. 288, are generally used for ordinary deep drawing work. For large articles, especially where the raising is considerable, hydraulic presses as in Fig. 289 are recommended, in which the speed of drawing can be varied between wide limits. In aircraft manufacture, draw presses as in Fig. 290 are used

Fig. 290.

Hydraulic draw-press with mounting for rubber punch (Fielding and Platt Ltd.).

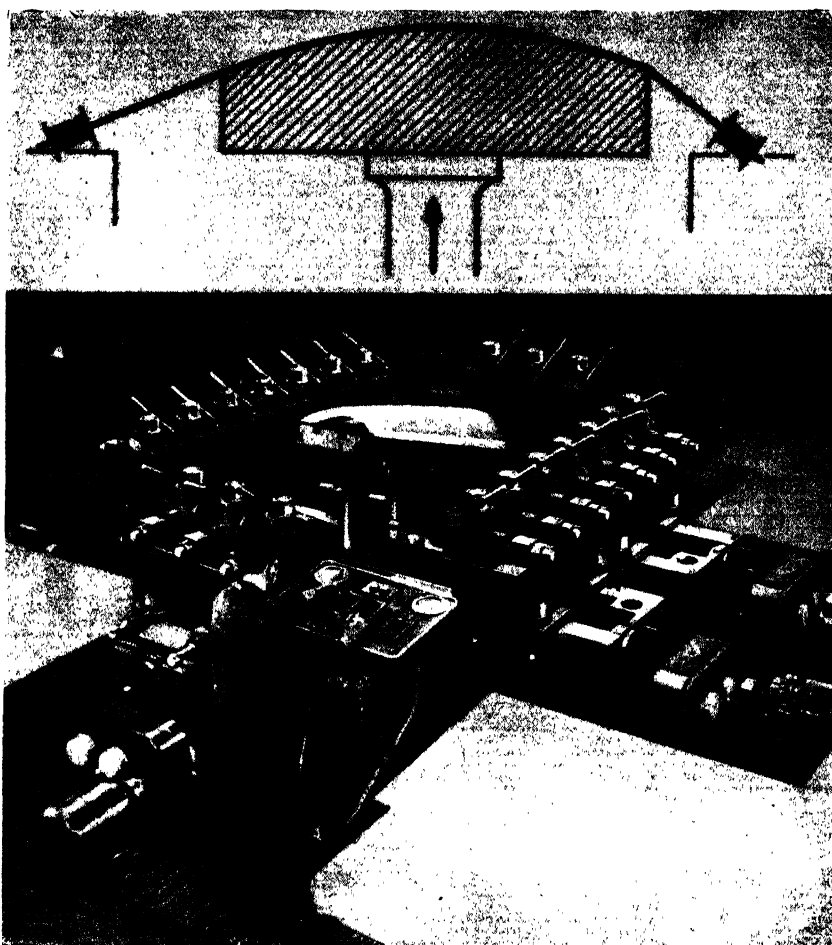


Fig. 291. below: Stretch-forming machine (Fielding and Platt).

Fig. 292. above: Stretch-forming — schematic.

for the repetition punching out of complicated shapes from sheets using a rubber punch. The shape required to be punched is accurately cut out in a steel plate and this is mounted on the platen of the press. On this is placed the aluminium sheet to be punched out. A punch of natural or artificial rubber is fixed to the cross-head of the press, and when this descends and the pressure thereby increases sufficiently, the rubber punch causes the light metal sheet to be punched out through the plate die below it.

For small runs, stretch forming is now frequently used instead of ordinary drawing. In this, a sheet is gripped on all sides in a stretch forming machine. Fig. 291 shows such a machine, with rectangular clamps arranged for adjustment to different sizes of rectangular sheets. After the sheet

has been firmly clamped on all sides, the former, usually made of hard wood, is pressed up against it from below by means of a hydraulic cylinder, and the sheet is formed to the required shape by stretching as the former rises into it, as shown diagrammatically in Fig. 292. Deep forming requires not only a number of drawing operations, as shown in Fig. 285, but when alloys are processed, intermediate annealing must be carried out owing to the rapid hardening up in the process. By increasing the number of draws, the number of intermediate anneals can be diminished. To make full use of the drawing capabilities of the strong heat-treatable alloys, annealing

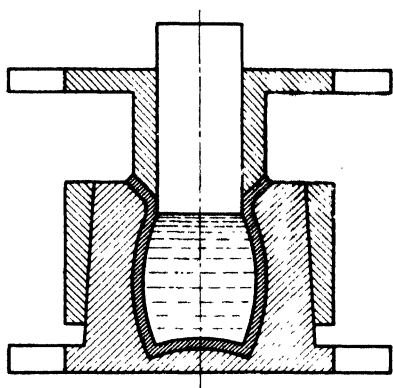


Fig. 293. Production of bellied vessel by water pressure.

must take place after every two draws.

For the production of bellied articles, a cylindrical shell is first drawn, then instead of a solid punch, hydraulic pressure is applied inside the shell, as shown in Fig. 293. The pressure water is generally brought directly into the drawing tools through the metal punch.

Deep stamping into a shaped die is now sometimes carried out with a rubber punch, this method being of comparatively recent introduction. For stamping, the rubber should have a hardness of 50-60 and for beading a hardness of

65 on the Shore scale. The depth of the rubber punch is usually about 8 to 12 inches and in many cases on the outermost 2 inches is of the special rubber of the desired hardness, while the interior part has a hardness of 65-70. The die is either cut in hard wood or made of a zinc casting (96% zinc, 4% copper). Since oil and grease attack rubber, French chalk or graphite are generally used for lubrication of the stock.

## CHAPTER XIII : THERMAL PROCESSES

### 1. TYPES OF THERMAL PROCESS

Three different types of thermal process are applied in the manufacture of light metals, namely:

Reheating of billets and blocks for forging, extrusion and hot rolling.

The heating up from the cold of wrought pieces to regain their plastic deformability by annealing prior to the further working.

The heat-treatment of those alloys in which the properties are improved thereby, at the conclusion of fabrication, comprising the necessary solution heat-treatment and quenching for the purpose of improving the physical properties by precipitation hardening.

Each type of thermal process requires certain temperature ranges, which may vary according to the alloy, and which must be held within suitable limits. In Table 37 are given the required temperatures for various alloys in the various thermal operations. The table shows that in heat-treatment, the temperature must be held within the narrow limits of  $\pm 5^{\circ}$  to  $10^{\circ}$  C ( $\pm 9^{\circ}$  to  $18^{\circ}$  F). If the upper limit is exceeded, the material will be spoilt by "burning" or incipient fusion of the components, while if the lower limit is not attained, the hardening effect will not be fully developed and inferior tensile properties will result. Fig. 294 shows the microstructure

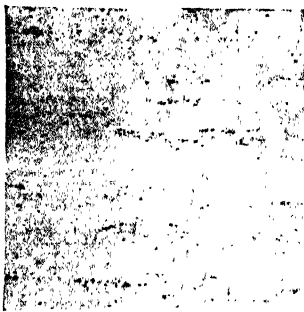


Fig. 294.  
Correctly heat-treated  
Duralumin—microsection.



Fig. 295.  
Duralumin over-heated in  
heat-treatment—microsection.

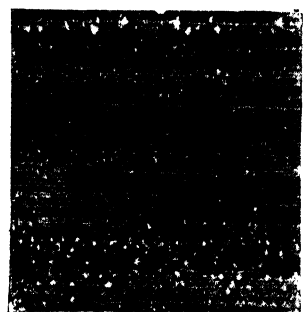


Fig. 296. Duralumin over-  
heated in heat-treatment—  
surface appearance.

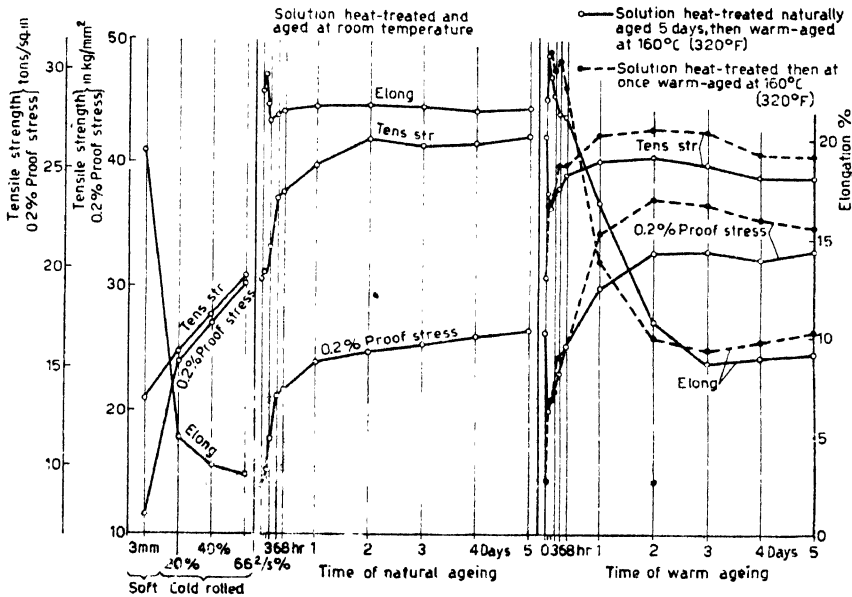


Fig. 297. Curves of mechanical properties as influenced by cold rolling and by precipitation hardening — Al-Cu-Mg alloy (Duralumin or Avional D).

of the Al-Cu-Mg alloy Avional (Duralumin) quenched from the correct heat-treatment temperature of  $505^{\circ}\text{--}515^{\circ}\text{C}$  ( $941^{\circ}\text{--}959^{\circ}\text{F}$ ), while Fig. 295 shows the effect of overheating to  $520^{\circ}\text{--}525^{\circ}\text{C}$  ( $968^{\circ}\text{--}977^{\circ}\text{F}$ ) on the structure of this alloy. Overheating is not always shown up by the formation of blisters (Fig. 296), as these may not be developed without further overheating to  $530^{\circ}\text{--}540^{\circ}\text{C}$  ( $986^{\circ}\text{--}1004^{\circ}\text{F}$ ), but incipient fusion and spheroidisation of the eutectic components will take place at temperatures slightly above the prescribed safe upper limit. The effects of overheating are shown first by a reduction in the bending and notched-bar impact strengths of the alloy, while impairment of tensile strength only takes place after overheating to more excessive temperatures.

Fig. 297 shows the curves of physical properties in cold working and in precipitation hardening of the Al-Cu-Mg alloy Avional (Duralumin). It can be seen that the increase of strength in cold working is accompanied by a considerable loss of elongation, while in precipitation hardening the elongation is not so greatly reduced. Also the cold working causes a greater proportional increase in proof stress than does precipitation hardening. Hardening by cold working followed by softening by annealing can be repeated as often as may be required on the same piece of material, provided the correct conditions are observed.

TABLE 37  
TEMPERATURES OF THERMAL TREATMENTS

Material (see Tables 3 and 4).	Annealing temperature	Heat-treatment		Hot working		Percentage cold reduction	
		Solution temperature	Precipitation temperature	Starting temperature	Lowest tempera- ture	Total between anneals %	Max. per pass %
Pure aluminium . .	360—400°C (680—752°F)	—	—	450—500°C (842—932°F)	350°C (662°F)	70—95	50
Anticorodal wrought (Al-Si-Mg)	360—400°C (680—752°F)	530—550°C* (986—1022°F)	155—160°C (B) (311—320°F)	480—520°C (896—968°F)	400°C (752°F)	60—85	25
Anticorodal (Cast — 5% Si) (C: Al-5Si-Mg).	—	510—530°C (950—986°F)	155—160°C (B) (311—320°F)	—	—	—	—
Alufont 3 (C: Al-Cu-Ti) . . .	—	525—535°C (977—995°F)	140—145°C (A) (284—293°F) 155—160°C (B) (311—320°F)	—	—	—	—
Avional D (Al-Cu-Mg) . . . .	360—400°C* (680—752°F)	505—515°C (941—959°F)	Room temp.	400—450°C (752—842°F)	360°C (680°F)	60—85	20
Avional M.S. (Al-Cu-Mg) . . . .	340—370°C* (644—698°F)	495—505°C (923—941°F)	Room temp.	400—450°C (752—842°F)	360°C (680°F)	60—85	20
Aluman (Al-Mn) .	450—500°C (842—932°F)	—	—	450—500°C (842—932°F)	450°C (842°F)	60—85	25
Peraluman 3 (Al-3Mg) . . . . .	360—400°C (680—752°F)	—	—	400—450°C (752—842°F)	400°C (752°F)	40—60	15
Peraluman 5 (Al-5Mg) . . . . .	300—400°C (572—752°F)	—	—	330—360°C (626—680°F)	330°C (626°F)	30—50	15
Silumin Gamma (C: Al-12Si) . . . .	—	500—510°C (932—950°F)	145—155°C (293—311°F)	—	—	—	—

\* Higher for thick sections.

A = Semi hard.

B = Full hard.

## 2. SOURCES OF HEAT

We will now consider the means of heating applicable to thermal processes. The oldest fuel, wood, was displaced in quite olden times by charcoal, then coal and finally coke. In modern times, oil and gas have been added to the list, and electricity, the most recent addition, has become an important source of heat, especially in those countries where fuel is scarce. In the selection of a fuel for heating material of high value, such as light alloys, we must consider not only the bare cost of the fuel, but also its effect on the charge, the efficiency and rapidity of temperature control and the uniformity of the temperature conditions obtainable. The solid fuels in

general do not satisfy these conditions, especially as regards uniformity of temperature and the accuracy of its control. With the at one time widely used semi-gas firing, the partly combusted gases together with the secondary air were admitted at one end of the furnace from below and were taken off near the charging door. In such a furnace it is scarcely possible to avoid higher temperature at the firebox end of the furnace than at the opposite end. Furthermore a quick curtailment of the heat input to the charge when it attains the maximum required temperature is rendered impossible by the existence of the glowing mass of coke. Oil firing permits much better temperature control and, with this fuel, a much more uniform heat distribution can be obtained over the entire furnace by a suitable disposal of burners. Oil firing however has a disadvantage in that its products of combustion frequently give rise to a staining of the stock which is usually too readily disregarded. This can be simply avoided by the use of a closed muffle in which the stock is not in contact with the combusting gases, but this arrangement, though it gives a still greater uniformity of temperature, obviously does so at the cost of the furnace efficiency. Still better results are obtained with gas firing. When town's gas is used, its higher purity prevents contamination of the stock. The simplicity of construction and control of gas burners, and the possibility of building the burners in the brickwork with so called burner blocks, permit a subdivision of the heat such that the required uniformity of temperature is assured.

The working temperatures required in thermal processes lie between  $300^{\circ}$  and  $550^{\circ}$  C ( $572^{\circ}$  and  $1022^{\circ}$  F) which is a range eminently suitable for electric resistance heating. When an electric current is passed through a metallic conductor, there is a voltage drop proportional to the resistance of the conductor and to the current. Very good alloys for resistance heaters have now been developed which combine a high resistance with refractoriness up to high temperatures, and the best qualities will give very long service without scaling at temperatures as high as  $1300^{\circ}$  C ( $2372^{\circ}$  F). These resistance heaters make it possible to obtain absolutely uniform distribution of heat over the entire furnace space. When the current is cut off, the liberation of heat ceases instantaneously and the small mass of the resistance elements only causes a very small overrun in the heat input. The liberation of heat by an electric heating element is directly proportional to the units of electrical energy consumed, in the ratio of 1 kWh to 860 kcals or 3414 British Thermal Units (B.Th.U's). At a uniform voltage and constant furnace temperature, the current passed by an electric heating element is constant. For temperature control, therefore, either the voltage must be changed, or some of the elements must be cut in or out as the case may require. As the control gear required for voltage control is expensive, the second method is usually adopted. With this system the heater groups



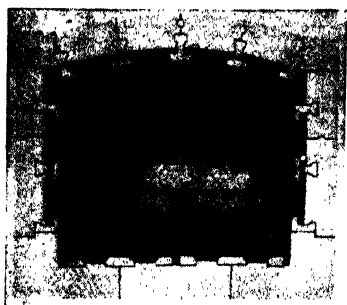


Fig. 298.  
Electric annealing furnace with  
support bricks for heating elements.  
contacts as in a so called stretch-annealing machine as shown in Fig. 313.

### 3. TYPES OF FURNACE

The type of furnace used depends on the process to be carried out, and the shape of the stock to be processed. For the reheating of blocks or billets, the size, shape and number of pieces required per hour determine the choice of furnace. With large sized blocks or billets, conveyor furnaces are suitable, in which the cold blocks are charged at one place and travel through the furnace with the motion of the conveyor, being heated to the required temperature in passage by the time they come to the discharging door to be taken out for the next operation. In conveyor type furnaces, the temperature does not have to be uniform over the entire heating chamber. The temperature has to be so controlled, however, that the

must be uniformly distributed over the furnace as shown for example in Fig. 298. Electric heating has the great advantages in annealing and heat-treatment of cleanliness, thermal uniformity and instant control. The most recent development is the use of induction heating, whereby an electric current is induced in the charge itself, which is thus heated solely from within itself and not by any external resistance heaters whatever. In another method electric current is led into the stock by suitable

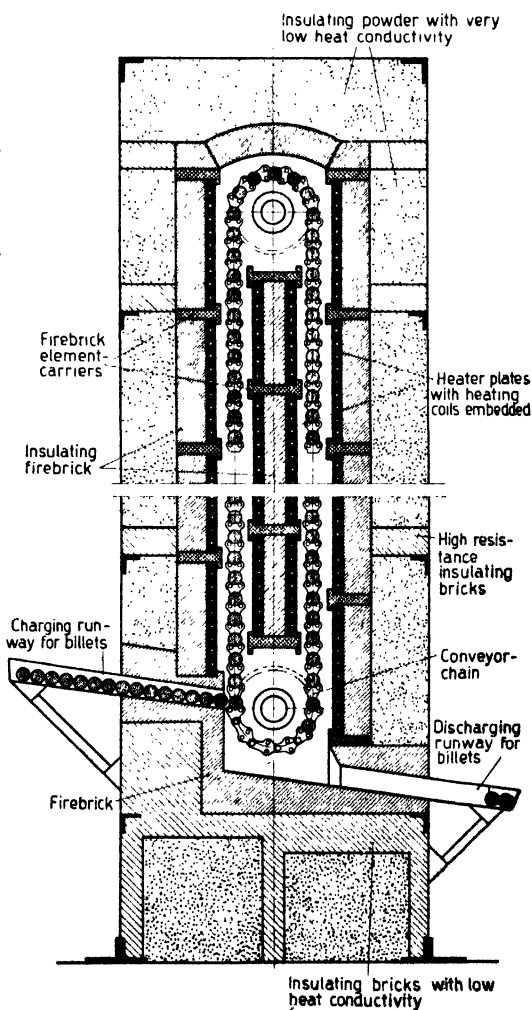


Fig. 299. Paternoster billet heating  
furnace (Junkers).

blocks or billets always come out at the correct temperature. To save floor space, continuous conveyor furnaces are sometimes built of the so called Paternoster type in which the blocks are elevated on a conveyor chain to the top of a vertical shaft furnace and descend on the other side to the discharging door at the bottom (Fig. 299). To cut down the duration of heating in continuous furnaces, it is common practice to work the furnace at a higher temperature at the charging end, at which cold blocks are charged, than at the discharging end, at which the temperature must be accurately held at the prescribed value.

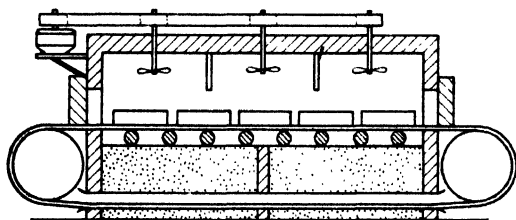
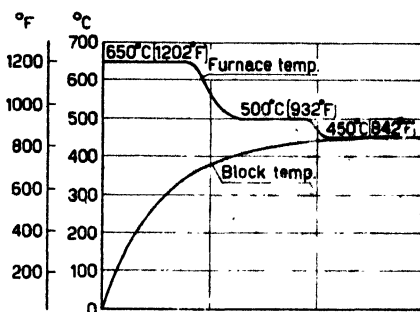


Fig. 300. Temperature curves for electric block heating furnaces.

Fig. 300 shows graphically the temperature distribution in a furnace operated under such conditions, also the heating curve of the rolling blocks during their passage through the furnace. When the rate of discharge of blocks is not uniform, as for instance when it is interrupted by a breakdown on the hot rolling mill, the heat input into the furnace must be controlled correspondingly. It is usually found that there is a fall of temperature near the charging door owing to the increased heat-loss through it. In a case such as the reheating of forging blanks for instance, in

which the furnace door has to be opened frequently to take out the stock, there is a loss of temperature in the region of the door after the discharging of the furnace begins and it becomes impossible to bring the material to the hammer at the correct starting temperature for forging. If the loss of temperature is compensated for by a general increase in heat input, there is a danger that the blocks or blanks further in the furnace become overheated, unless a special group of heating elements is provided to give only a locally intensified heat input in the immediate vicinity of the door. Such a heater group must of course be provided with its own temperature measuring apparatus and temperature controller. This condition also applies in the case of continuous furnaces, where an accurate temperature indication and regulation is necessary. To expedite homogenisation in blocks and billets, reheating is often started at a higher temperature, the alloy then being cooled down slowly to hot working temperature. Avional (Duralumin)



Fig. 301. Pit furnace for solution heat-treatment of propeller blades  
(Wild-Barfield Electric Furnaces Ltd.).

blocks for instance, which are hot rolled at  $450^{\circ}\text{C}$  ( $842^{\circ}\text{F}$ ) max., are gradually heated up to  $500^{\circ}\text{C}$  ( $932^{\circ}\text{F}$ ), being then left several hours in the furnace to cool down slowly to  $450^{\circ}\text{C}$  ( $842^{\circ}\text{F}$ ), at which temperature working may begin.

Furnaces for annealing material in preparation for further cold work are generally of the batch type rather than the continuous type. In the batch type, a considerable load is charged in the furnace at one time and is heated up to the prescribed annealing temperature, at which it is allowed to remain for a sufficient time to complete the annealing, when it is discharged and replaced by a fresh charge. Batch type furnaces must attain a uniform temperature at all points in the chamber so that all pieces of the charge shall be uniformly annealed. This condition must also obtain in the case of heat-treatment furnaces (Fig. 301) and indeed in these the temperature control and distribution must have a high degree of accuracy owing to the very narrow temperature tolerance permissible. As the maximum temperatures required in annealing furnaces do not exceed  $550^{\circ}\text{C}$  ( $1022^{\circ}\text{F}$ ) a refractory brickwork construction is not required and the furnaces can be built simply with double sheet steel walls with heat insulating material filling the space between, the electric heating elements being fixed to the interior heat-resisting sheeting. Furnaces built in such a way have the advantage of a lower heat capacity and quicker heating up, furthermore they may be moved about without great difficulty.

In earlier practice it was assumed that the air in the furnace constituted the medium of heat transfer to the charge. Air, however, is not an ideal medium. Its low specific heat and low thermal conductivity cause the heating of the charge to be very slow, and temperature differences are only

slowly equalised. These disadvantages have been alleviated by setting the air in motion. If a sheet of aluminium alloy 0.80 inch thick is hung up in a hot heat-treating furnace at  $500^{\circ}\text{C}$  ( $932^{\circ}\text{F}$ ) it requires 35 minutes in still air to heat the sheet to  $498^{\circ}\text{C}$  ( $928^{\circ}\text{F}$ ). If the air is circulated at a velocity of 6 feet per second, the heating time is reduced to 18 minutes, while at 15 feet per second the time is 12 minutes. In air circulation furnaces however, care must be taken that there are no dead spaces. These might be caused either by the shape of the furnace or by the shape and disposition of the charge, and they have the effect that the heating in the stagnant places is much slower and the required temperature might not be arrived at. Thus, air circulation does not give complete certainty. Another factor that may cause irregularities of heating is the effect of the surface condition of the charge. Heat transfer is the lowest in cold rolled or machined bright metal surfaces. Even the presence of the oxide skin formed in casting increases the rate of heat transfer.

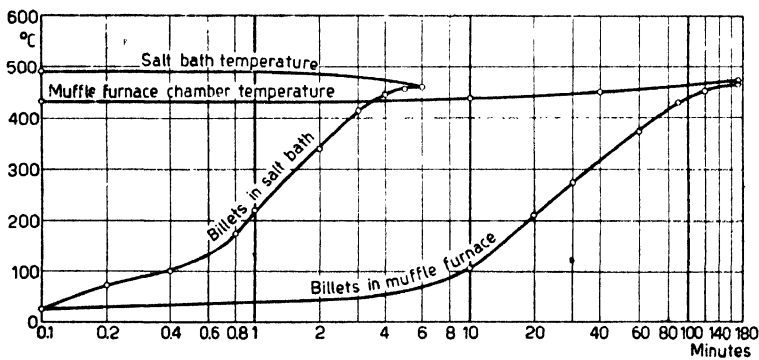


Fig. 302. Heating curves for al. forging billets, 4 in. diameter, 8 in. long, 9 lb. weight, in salt bath and muffle furnaces — log. time base.

If, instead of air, a liquid medium for heat transfer is used, the temperature uniformity and heat capacity are both considerably increased. Everybody knows how quickly a uniform temperature can be obtained in a hot bath by merely stirring the water. For processing temperatures up to  $200^{\circ}\text{C}$  ( $392^{\circ}\text{F}$ ) oil can be used as the liquid medium. For higher temperatures fused mixtures of salts are used, a mixture of potassium and sodium nitrates in proportions of 1 to 3 being preferred, the melting point of this mixture being  $270^{\circ}\text{C}$  ( $518^{\circ}\text{F}$ ), while it is suitable for use up to  $530^{\circ}\text{C}$  ( $986^{\circ}\text{F}$ ). At higher temperatures these salts begin to volatilise and to decompose. In recent years it has been a common practice to make an addition of 2% of sodium monochromate  $\text{Na}_2\text{CrO}_4$ , to the original sodium-potassium nitrate mixture used in salt baths. This addition exerts a protective action on the tank itself and also on the aluminium alloy material under treatment. Since nitrates tend to decompose to nitrites, especially

under conditions of overheating of the bath, with the formation of dangerous decomposition products, the practice has been adopted of using a salt mixture of 90% sodium nitrate with 10% sodium nitrite. This has less tendency to decompose and can be used up to a temperature of  $540^{\circ}\text{C}$  ( $1004^{\circ}\text{F}$ ). Salt baths have the advantage of a high heat capacity and high degree of uniformity of distribution of temperature, but they have the disadvantage that the stock is contaminated with salt, which necessitates a careful washing and cleaning of the material after heat-treatment; in addition the unavoidable loss of salt which amounts to about 1 lb. per 30 to 70 square feet of surface heat-treated, increases the cost of the process. Fig. 302 shows the heating up of a forging billet 4 inches diameter and 8 inches long to  $450^{\circ}\text{C}$  ( $842^{\circ}\text{F}$ ). This takes 150 minutes in an air furnace, but in a salt bath the metal reaches temperature in 6 minutes. If the salt bath is used for the purpose of solution heat-treatment, generation of steam from the quenching water always takes place in the quenching operation, and this transports some of adhering salts into the atmosphere, and redeposits it on surrounding objects. This salt exerts a corrosive effect on aluminium and therefore a salt bath shop must always be a very well ventilated building, and the aluminium alloy stock should be taken out of it immediately after quenching and washing. It is well known that the nitrates of soda and potash are powerful oxidising agents, and that a mixture of either with carbon constitutes gunpowder. Inflammable substances such as oil, grease, wood, etc., that may contaminate the metal and be immersed with it in the molten salt at  $500^{\circ}\text{C}$  ( $932^{\circ}\text{F}$ ) give rise to an immediate small explosion, which may blow a quantity of molten salt out of the bath. In fuel-heated salt baths, when the walls of the iron bath became worn thin, the molten salt may leak out with a danger of a powerful explosion if it comes in contact with the fuel. Not only inflammable substances, but also water that may be taken into the molten salt may lead to explosion due to generated steam and decomposition, with the blowing out of molten salt. As stated

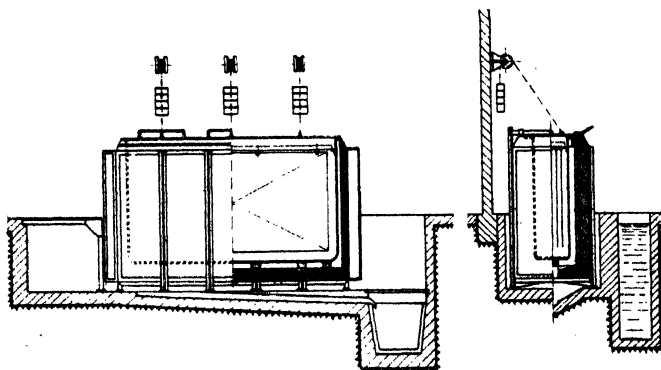


Fig. 303. Electric salt bath furnace.



Fig. 304. Air-circulation electric muffle furnaces for sections and tubes (Metaelectric Furnaces Ltd.).

above, overheating of the salt to over  $530^{\circ}\text{C}$  ( $986^{\circ}\text{F}$ ) causes decomposition which gives rise to a rapid attack on the walls of the iron bath, which condition is therefore to be rigidly avoided. This demands an absolutely reliable control and uniformity of the heating. Electric heating (Fig. 303) has a great advantage in this respect. The latest practice is to have internal tubular heaters submerged in the molten salt, the heating elements being contained in metallic tubes. The iron baths suffer less attack when this type of heating is employed, as the heat does not have to be transmitted through the walls of the bath.

A reliable temperature control, preferably automatic, ensuring a steady temperature whether or not the salt bath is in use, is essential owing to the

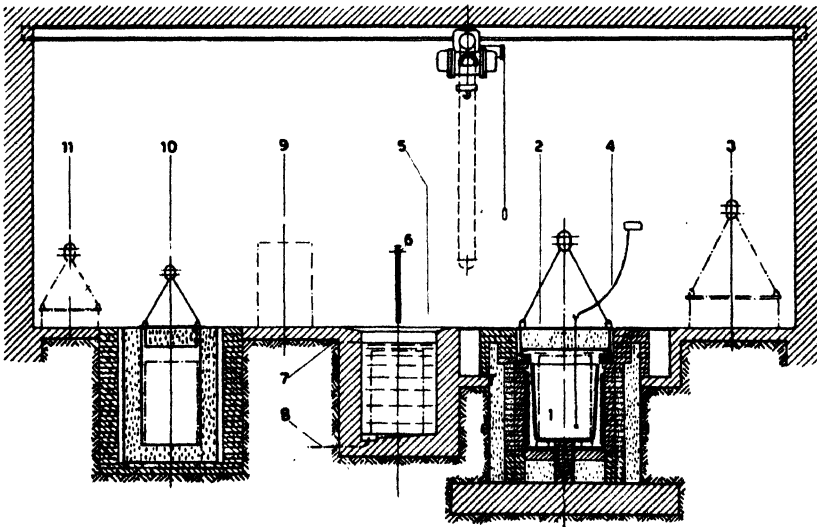


Fig. 305. Lay-out of heat-treatment plant.

1. Pit furnace for solution heat-treatment
2. Cover of pit furnace
3. Cover removed
4. Pyrometer flex
5. Quenching tank
6. Cold water supply
7. Overflow
8. Drain plug
9. Load basket for charging into the solvent or ageing pit furnaces
10. Ageing furnace (pit type)
11. Cover of ageing furnace removed

risk otherwise of spoiling the work, decomposing the salt and thereby attacking the iron of the bath at temperatures over  $530^{\circ}\text{C}$  ( $986^{\circ}\text{F}$ ). When the salt bath is in use, a sediment accumulates at the bottom. This necessitates the cleaning out of the salt bath once every two months, for which it is completely emptied off by baling, and the residual sludge removed. On the occasion of cleaning, the iron walls are tapped to test their condition, and any weak places repaired by welding.

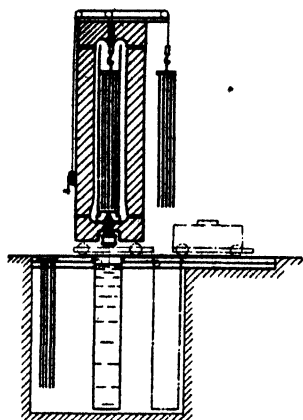


Fig. 306.

Vertical heat-treatment furnace for sections and tubes.

The dimensions of the furnace are governed by the shape and size of the charge to be heated. For sections and tubes, muffle furnaces as in Fig. 304 are used, and for bulky articles, either muffles or pit furnaces (Fig. 305). For long pieces such as rods, sections or tubes, tubular furnaces may also be used, which can if required be arranged vertical so that the charge can be suspended vertically in them (Fig. 306). Special purpose furnaces include continuous furnaces for mass-production heat-treatment, such as is shown in Fig. 307. In all these furnaces uniform distribution of temperature and accurate control of the same is a predominant factor in successful operation.

#### 4. EFFECT OF HEATING AND COOLING

In solution heat-treatment furnaces, not only are accurate temperature conditions important, but also rapidity of heating, if a fine-grained product is to be assured. As shown in Fig. 308, the solution treatment of sheets in salt baths gives a much finer grain-size than treatment in an air furnace,

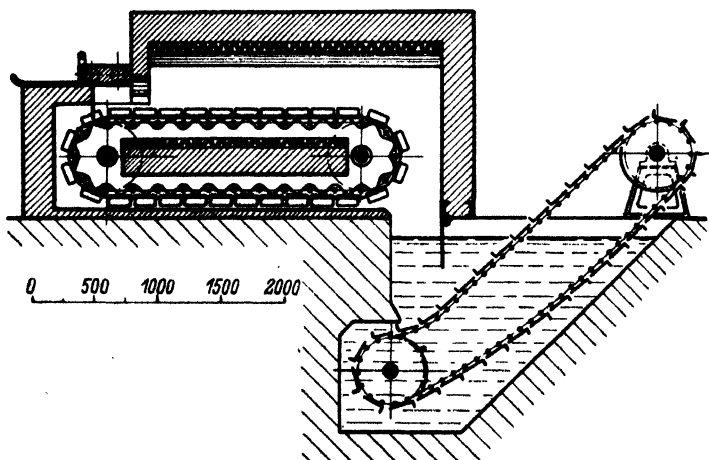


Fig. 307. Electric heat-treatment furnace with chain conveyor and quenching pit.

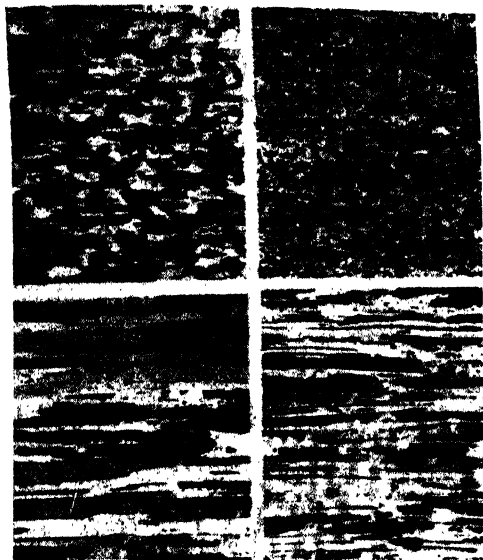


Fig. 308. Effect of rate of heating in solution heat-treatment on grain-size.

Left: Air furnace, Right: Salt bath, Above: Structure of rolled material, Below: Structure (longitudinal) of extruded material.

despite the fact that, in furnaces of the latter type with high velocity air circulation and suspended sheets, the charge is heated to temperature in 10 minutes. In comparison with this the salt bath brings the metal up to temperature in a matter of seconds.

Magnesium alloys must not be treated in a nitrate salt bath, as there is a risk of explosion with this metal. They may either be treated in a fused chromate bath, which is expensive, or in muffle furnaces. Owing to the tendency of magnesium to oxidize at the annealing temperature, an atmosphere of sulphur dioxide is employed, which requires a tightly sealed furnace (Fig. 309).

In the heat-treatment of castings, owing to the coarse grain of the cast

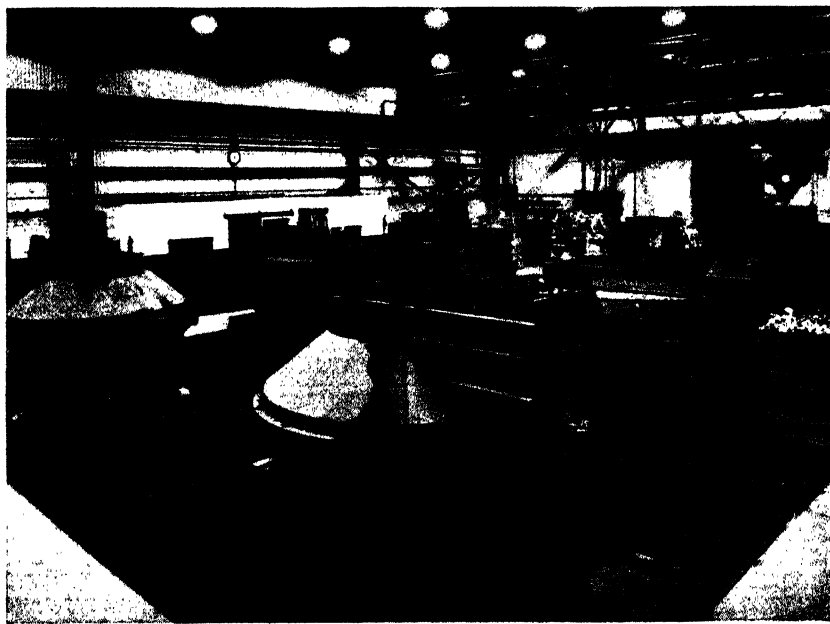


Fig. 309. Annealing furnaces with controlled atmosphere for Mg alloys. J. Stone & Co. Ltd.



structure a much longer duration of heating is required than for wrought material. To carry out solution treatment to completion on castings, a duration of 5 to 24 hours is required depending on the alloy and the type of casting, whether sand or die casting. Diversity of section thickness in a casting renders a rapid heating dangerous, such as in a salt bath, owing to the generation of thermal stresses, and in consequence air furnaces are

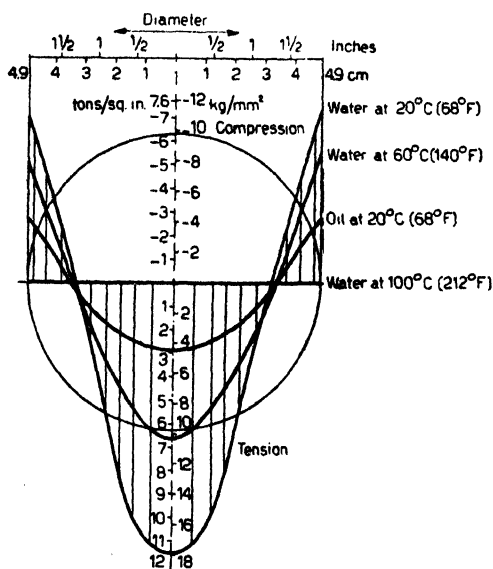


Fig. 310.

Curves of quenching stresses in a round rod.

In quenching, stresses arise through uneven cooling, which cause a distortion of the articles. In thick walled articles, the portions that cool slowest internally contract only with elastic strain. Due to this, the interior portions of thick pieces are stressed in tension, and the surface in compression. These stresses vary according to the speed of quenching, whether in cold or hot water for example. Rectification of the shape is done by a subsequent light working. Fig. 310 shows the quenching stresses in 4 inch diameter Al-Cu-Mg (Duralumin) round alloy rods quenched from 500°C (932°F) in water of 20°, 60° and 100°C, (68°, 140° and 212°F) and in oil at 20°C (68°F).

## 5. TEMPERATURE MEASUREMENT

It is obvious from the foregoing that correct furnace practice necessitates reliable and accurate means of temperature measurement. For the range of temperature in question, i.e., 150° to 550°C (302° to 1022°F), thermo-electric pyrometers are the most suitable, though dilatation thermometers

advantageous for this purpose. In the heat-treatment of castings it is to be noted that the strength at the maximum temperature is only very low, and thus to prevent distortion in large castings, they are loaded in iron baskets. Salt bath treatment has the advantage here in that the virtual weight of the casting is reduced to about half owing to the buoyancy of the salt. The latest American practice for heat-treatment favours the employment of high velocity air circulation furnaces, which have the advantage of lower operating cost owing to the avoidance of the salt loss.

may be used. For accurate temperature indication in industrial furnaces, the measurement of temperature at different points distributed over the entire furnace is necessary, and for furnaces of large hearth area there must be points of measurement in the middle of the arch, which are not easy of access from the hearth. The reading of thermometers installed in the furnace on such a scale would be a matter of great difficulty. Thermo-electric measurement, however, provides a simple system whereby the indications from any required number of measuring points may be read at one common point. The principle of the thermo-electric pyrometer is that, in a loop or circuit of two wires of dissimilar metals, one of the junctions between the metals is raised to a higher temperature than the other, under which condition an electro-motive force is generated which is propor-

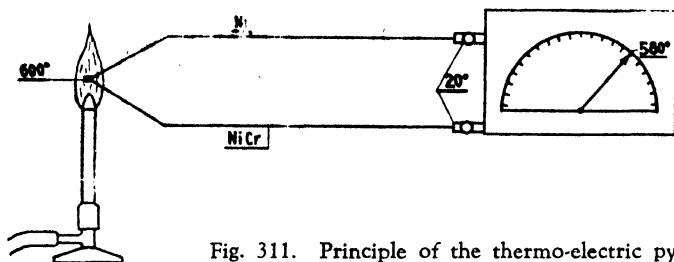


Fig. 311. Principle of the thermo-electric pyrometer.

tional to the difference in temperature between the hot and cold junctions. A sensitive millivoltmeter in circuit at the cold junction (Fig. 311) will give readings proportional to the difference in temperature between the junctions. Unlike the ordinary thermometer which always gives a true temperature reading in  $^{\circ}\text{C}$  (or  $^{\circ}\text{F}$ ), the thermo-electric pyrometer only gives the reading of the difference of temperature of the two ends of the wires, as above. To know the true temperature of the hot junction, it is necessary to read the true temperature of the cold junction with an ordinary thermometer and to add this to the indicated temperature difference. The cold junction temperature varies according to the ambient conditions, which are prone to fluctuate and to vary from place to place. The corrections necessary under such conditions would be troublesome, particularly when there are a number of points. This may be obviated by connecting compensating leads to the thermo-element wires, which compensating leads have no thermo-electric force in themselves against wires of the thermocouple. The compensating leads are all led to a central point where the cold junctions of such circuit are located in a so called equalising pot. This greatly facilitates the observation of the cold junction temperature as there is only one thermometer. The cold junction control can be made simpler still by providing automatic thermostatic temperature control for

the cold junction equalising pot (Fig. 312). This can be done by having an electric heater with an automatic thermostat switch which can be set to maintain a suitable temperature of say  $40^{\circ}\text{C}$  ( $104^{\circ}\text{F}$ ), to which correction the millivolt indicator can be permanently set. Fig. 312 shows such a system of temperature measurement on an electric annealing furnace. In the illustration a recorder is shown, beside the ordinary indicator, the former

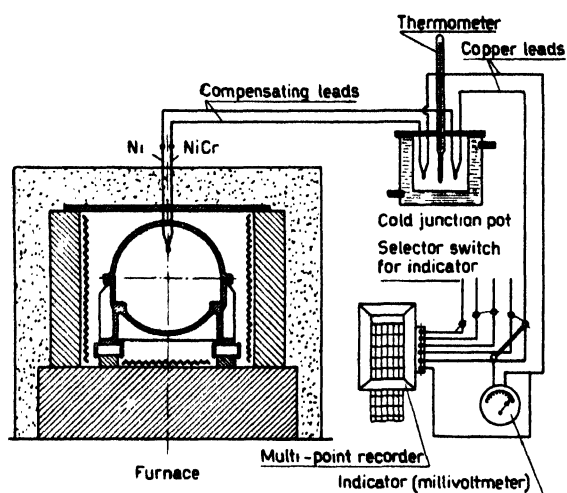


Fig. 312. Pyrometer for annealing furnace.

being connected with six different measuring points in the furnace in turn by means of an automatic commutator, the records being multi-coloured, with a different colour for each circuit. In some cases only one element of the thermocouple is separately connected to the indicator, a common lead being used for the other element of all couples in the system. This arrangement entails some risk of inaccuracy arising from the opposing effects

of the thermoelements and extraneous induction effects and is not recommended. Both poles of all thermo-couples should be independently connected to the indicator, and double-pole commutating switches used. For temperature measurements up to  $550^{\circ}\text{C}$  ( $1022^{\circ}\text{F}$ ) the resistance pyrometer as originally introduced by SIEMENS has again been brought into industrial use. In this instrument, a platinum spiral of 100 ohms resistance, about  $1\frac{1}{4}$  inches long and fused in refractory glass, is used as the means of temperature measurement instead of the thermocouple hot junction. An automatic resistance bridge enables the change of the resistance of the platinum spiral, which is proportional to temperature, to be used as an indication of temperature. The big advantages of this method of measurement lie in the elimination of a cold junction and in the sensitivity and constancy of the platinum resistance pyrometer. It is therefore to be anticipated that resistance pyrometers will displace thermo-electric pyrometers to an increasing extent. Small plants sometimes do not have electric pyrometers. In order to exercise some control over temperature in such cases (which may include small forging plants for instance), use is made of some simpler if less accurate method. For the lower temperatures such as are shown in Table 38, a small quantity of sugar thrown on the article whose

TABLE 38  
TEMPERATURE INDICATORS

Approximate temperature		Fir or pine wood	Soap	Sugar
°C	°F			
160—170	320—338	—	—	Sugar melts
170	338	—	—	Sugar remains colourless for 1 min.
180	356	—	—	Sugar colourless for 30 seconds yellowish in 1 minute
200	392	—	—	Sugar yellowish in 5 seconds, golden yellow in 20 seconds
225	437	—	—	Sugar yellowish in 2 sec., golden yellow in 5 sec.
250	482	—	Yellowish in 10 to 20 sec.	Sugar golden yellow immediately
300	572	— *	Yellow in 5 to 10 sec.	—
350	662	Slow rubbing with moderate pressure leaves bright brown streak	Brown in 5 sec., dark brown in 30 sec.	—
400	752	Slow rubbing under light pressure leaves brown streak	Black in 10 sec.	—
450	842	Slow rubbing under light pressure leaves a dark brown streak, a quick light rub a light brown streak	Black in 5 sec. and dried up in 10 sec.	—
500	932	Quick light rubbing gives a black streak which disappears in 5 to 10 sec.	Black in 1 sec. and dried up	—
550	1022	A black streak disappearing in $\frac{1}{2}$ —1 sec.	—	—
Over 550	Over 1022	The black streak disappears immediately and the wood splint ignites.	—	—
	*	Oak gives a brown streak at 300°C (572°F) and a brown black to black streak at higher temperatures.	—	—

temperature is to be estimated gives good indication of required temperatures from 170° to 250°C (338° to 482°F). At higher temperatures up to 450°C (842°F) the colour of hard soap smeared on the metal shows its temperature, and from 350 to 600°C (662—1112°F) a dry fir or pine stick can be used. Another method is the use of the so-called thermo-colour crayons which show a sudden change of colour at certain temperatures. In one type, the colour returns to the original on cooling, while in another the colour change persists.

## 6. ERRORS IN TEMPERATURE MEASUREMENT

The sensitivity of thermo-electric pyrometers is from some points of view a disadvantage, as there are many points in the system from the hot junction to the pointer of the indicator where errors may originate. To avoid these, constant inspection and necessary adjustment are required, the points calling for attention being explained below. As already stated, an uneven distribution of temperature may obtain in the furnace. The first task in setting a new furnace to work is therefore to ascertain the temperature distribution accurately by taking numerous temperature readings at different points and with different loadings including empty, also at different degrees of temperature and under different thermostatic settings, in order to determine whether uniform conditions of temperature exist throughout the furnace under all conditions of loading. Should this not be the case, the uniformity of temperature must be improved by a suitable rearrangement of the heaters. It is often found that there is a lower temperature in the region of the door or at the back end, and if this is so, additional heaters to compensate the local deficiencies should be installed. When it has been ascertained that the temperature distribution is correct, the location of the control thermo-couple must be examined for suitability of position. It may be found that the control couple is located too near the heating elements and thus only responds at a higher temperature than is required in the furnace. The next error is the use of incorrect compensating leads. The compensating leads must be accurately matched to the material of the thermo-couple elements and must be connected the right way round to the thermo-couples, for which the elements mostly used are nickel, nickel-chromium. If the compensating leads have been connected the wrong way round, a doubling of the error of the cold junction temperature would result.

Thermo-couples are usually protected against mechanical damage and the effects of the furnace gases by sheathing in steel or ceramic tubes. These sheaths however cause some conduction of heat away from the couple, depending on the depth of immersion and the conductivity of the

material. When sheathed couples are used, therefore, it is necessary to check the difference in temperature between the interior of the sheath and that of the surrounding atmosphere.

A further temperature error may arise through the slow penetration of heat into the annealing charge, which in cases of large charges, such as high stacks of sheets, may be rather pronounced, requiring a considerable time for the middle of the charge to come up to the furnace temperature. It is advisable in such a case to insert a special thermo-couple as near as possible to the middle of the charge, so that the penetration of heat can be accurately observed. Between the hot junction and the millivoltmeter which indicates the thermo-electric force, there is a very small voltage drop due to the resistance of the circuit, which is proportional to the resistance of couple and leads and is inversely proportional to the internal resistance of the millivoltmeter. The millivoltmeter should therefore always have an internal resistance of not less than 200 ohms. Again, the connections of the millivoltmeter should receive attention as the resistance of these may alter and necessitate the recalibration of the whole installation. In any case there should be a routine calibration check of all pyrometers at least once a month. It is often found that a lag develops in the millivoltmeter due to the slow accumulation of dirt and an overhaul then becomes necessary. As the cold junction temperature must be constantly controlled, it is necessary to check it from time to time, even if it is thermostatically controlled, as even a thermostat can go wrong. The cost of production in a single furnace charge is considerable and may be as much as £ 50 sterling or more, and this may be sacrificed and the whole charge be ruined by an excess of temperature of no more than 10°C (18°F), so that the cost incurred in looking after the pyrometric installation properly is always fully justified. The limit of error in the pyrometers permissible for a high standard of process control is  $\pm 3^\circ$  to  $\pm 6^\circ\text{C}$  ( $\pm 5^\circ$  to  $\pm 11^\circ\text{F}$ ) according to the accuracy of the instrument. With resistance pyrometers, the error, owing to elimination of the cold junction, can be reduced to 1 to 2°C (1.8 to 3.6°F). The process temperature should not be permitted to rise quite to the safe top limit, in order that this should not be exceeded if the instrumental errors are near the limit of the accepted degree of accuracy.

It will appear from the foregoing article that a pyrometric installation complete with accessories is fairly complicated. As, however, these installations are usually not in charge of skilled tradesmen, their construction should be as simple as possible, and faulty contacts, faulty insulation and instrumental errors should be eliminated as far as possible.

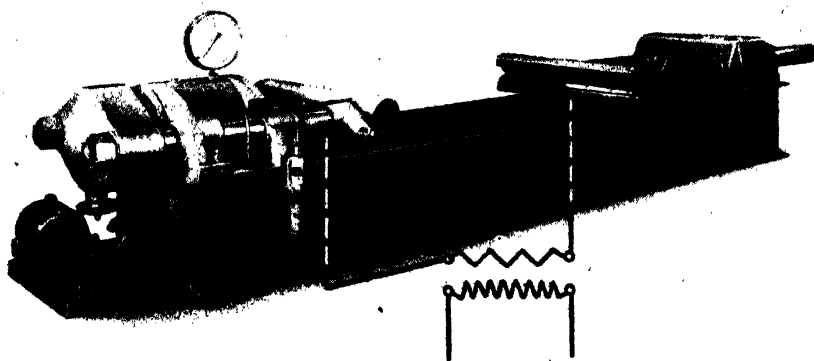


Fig. 313. 100 ton stretcher-levelling machine for sheets (Truninger).  
(with circuit diagram for stretch-annealing, p. 240.)

#### 7. RECTIFICATION

When a charge of light alloy material is lowered into a salt bath, it is not heated quite simultaneously and equally over all its extent. The first portion to go into the salt of course heats up and in doing so expands and softens, while the portions which have not entered the salt up to that moment retain their dimension and properties. This gives rise to stresses in the material which cause it to distort. This phenomenon repeats itself in reverse and to an increased degree in the quenching operation, and the material after quenching is always more or less deformed. In castings, the deformation is but little, with forgings it is somewhat greater, depending on their size and section, while with extruded or rolled materials distortion is considerable.

The rectification of the shape can be done in different ways alone or

in combination. The simplest straightening process is stretching, or stretcher-levelling as it is also termed. As shown in Fig. 313, the piece to be straightened is gripped at its ends in the jaws of the stretching machine. A pull is exerted on the piece by means of a hydraulic cylinder,



Fig. 314. Section stretching machine with detwisting head  
(Fielding and Platt Ltd.).

whereby it is extended by about 1% of its length, which extension causes all deformation parallel to the direction of stretching to be smoothed out. For dealing with sections, which are frequently twisted as well as bent, one stretching head is often made capable of rotating (Fig. 314) so that straightening and detwisting of the section can be carried out simultaneously. As the stock varies in length, one head of the stretching machine must be movable. In the machine illustrated, the moving head can be anchored to the bed in various fixed positions, but in other types of machine the moving head is traversed by lead screws. With the screw adjustment the head can be readily adjusted to any position, while a certain initial degree of tension can be applied to the stock by the manipulation of the screws themselves. The screw adjustment thus has the advantage of a more expeditious operation of the stretching machine for stock of varying length.

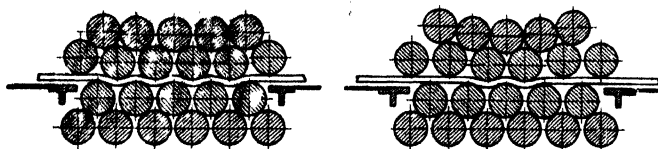


Fig. 315. Multiple-roller sheet levelling machine, backed-up type — diagrammatic.

Another widely used levelling process is roller levelling, carried out on roller levelling machines. These have multiple rollers and Fig. 315 illustrates the principle of the machine. The diameter of the rollers must be roughly proportioned to the thickness of the sheet to be flattened, thus for a large range of sheet thickness a number of machines of different sizes would be

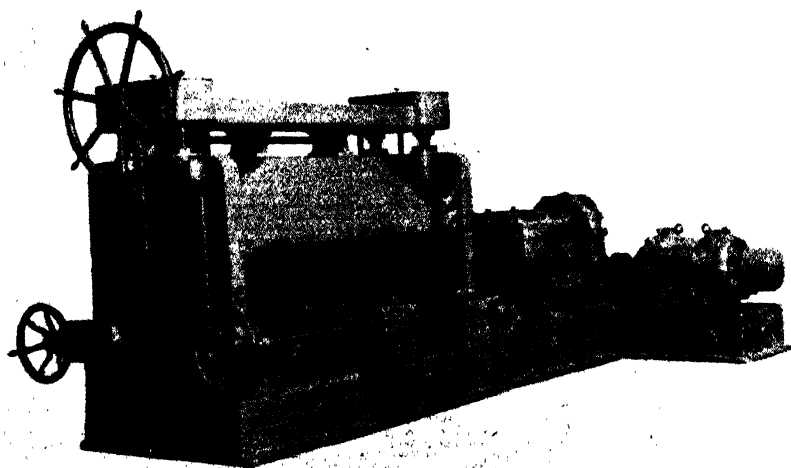


Fig. 316. Roller levelling machine for sheets (W. H. A. Robertson and Co. Ltd.).



required. To flatten sheets properly on these machines involves a good deal of experience on the part of the operator in adjusting the machine to the best advantage, and this may be a rather lengthy job. A typical machine is illustrated in Fig. 316. To permit flexure of the thin work rollers

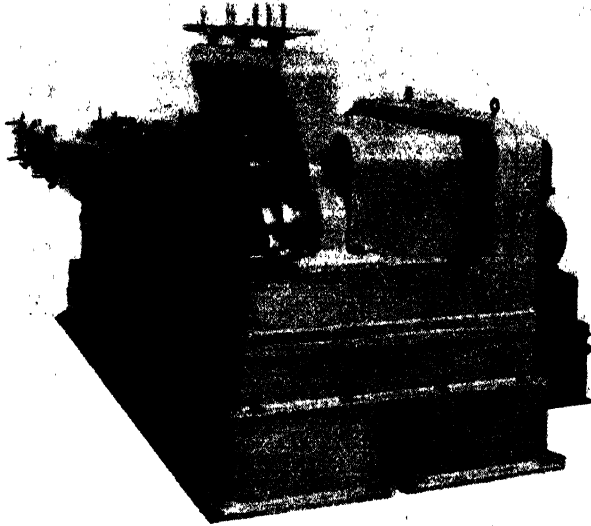


Fig. 317. Section levelling machine (W. H. A. Robertson and Co. Ltd.).

in the various modes that may be wanted, three sets of thin support rollers are provided which are mounted on massive yokes. These yokes can be raised or lowered independently as desired, whereby the work rolls are brought to the desired inclination and flexure. In the illustration, the safety,



Fig. 318. Reeling machine for rods and tubes (J. Bigwood and Son Ltd., Wolverhampton).

guards provided for the protection of the operator have been removed. For the roller-levelling of sections, the work rollers must be grooved to a shape conformable to that of the section. Sheet levelling machines may have 19 to 25 work rollers, but in section levellers the numbers of rollers is less (Fig. 317). For straightening round rods and tubes, a skew-roller rod-reeling machine is in common use (Fig. 318). These reeling machines are adjustable for a range of diameters of the stock.

In the case of sheets, flattening is usually completed by rolling on a planishing mill. For this operation it is advantageous for the sheet to have been rolled in the same rolls to 1 or 2% of the required finished gauge. A completely flat-rolled sheet, accurate and uniform to gauge over the whole cross-section, can be obtained with certainty by a final rolling or planishing operation without pressure on the rolls, using only the weight of the top roll to give its pressure on the sheet. Following the quenching operation, sheets are usually levelled in a roller levelling machine, then finally flattened, either on a sheet stretching machine or by roll planishing as above. The unavoidable small reduction in thickness caused by the flattening processes causes an increase in proof stress and a decrease in elongation and bend value.

## CHAPTER XIV: MACHINING PRACTICE

### I. GENERAL

The factors of importance in machining are:

- |                            |                          |
|----------------------------|--------------------------|
| a) The stock               | f) Tool life             |
| b) Tool shape and material | g) Rate of metal removal |
| c) Cutting force           | h) Cutting lubricant     |
| d) Shape of chip           | i) Operating cost        |
| e) Chip formation          | k) Work holding means    |

#### a. *The stock*

The heavy metals have a century of machining experience behind them. The mechanical properties of different materials as set out in Table 39 exhibit considerable differences as between light and heavy metals, as well as among the light metals themselves. This implies that different shapes of cutting tool must be used for the different materials. For machining on high speed automatic lathes, special alloys have been developed containing additions to promote the formations of short chips, such alloys being termed "free-machining". The "chip breaking" constituents in such alloys consist either of added low melting metals, such as lead or tin, or else hard brittle crystals resulting from the addition of iron or magnesium. With suitable tool shapes, however, all the harder light alloys can be satisfactorily machined on high speed automatic lathes.

#### b. *Tool shape and material*

The designations of the angles pertaining to the shape of cutting tools are shown in Fig. 319 and are ( $\alpha$ ) clearance ( $\beta$ ) cutting angle ( $\gamma$ ) top rake ( $\delta$ ) side rake. The tool angles are modified according to the hardness of the stock, as in Table 40.

TABLE 39

COMPARISON OF MECHANICAL PROPERTIES OF LIGHT METALS WITH THOSE  
OF COPPER, BRASS AND STEEL

(continued on page 260)

		.02 % Proof stress		Tensile strength		Elong- ation %	Brinell hard- ness	Modulus of elasticity	
		Tons/ sq. in.	1000 lb./ sq. in.	Tons/ sq. in.	1000 lb./ sq. in.			Tons/ sq. in.	10 <sup>6</sup> lb./ sq. in.
Pure Mg	soft	2.5	5.6	11	24	12	37	2670	5.9
(wrought)	hard	8	18	16	36	4	40	2670	5.9
Aviomag G9		7	16	17	38	11	57	2800	6.3
(sandcast C: Mg-9Al)									
Aviomag K6 Sheet		12	27	19	43	15	62	2800	6.3
Mg-6Al									
Pure Al	soft	2	4.5	5	11	30	20	4100	9.2
(99.5 %)	hard	9	20	10	12	5	35	4100	9.2
Anticorodal	soft	4	9	8	18	25	35	4400	9.9
Al-Si-Mg heat-treated		18	40	21	47	12	95	4400	9.9
Avional	soft	5	11	11	24	20	50	4400	9.9
(Duralumin)									
Al-Cu-Mg heat-treated		15	34	25	56	20	105	4400	9.9
Virgin copper	soft	5	11	14	31	43	18	7600	17
99.6 %	hard	23	52	25	56	3	110	7600	17
Brass (extruded)		11	24	27	60	33	95	7600	17
Mild steel rolled bar		16	36	25	56	25	115	12700	28

TABLE 40

TOOL ANGLES FOR DIFFERENT MATERIALS

Type of tool	Brinell hardness of aluminium alloy	Tool angles		
		Clearance ( $\alpha$ )	Cutting angle ( $\beta$ )	Top rake ( $\gamma$ )
Tool steel tools	up to 50	8—10°	30—50°	52—45°
	50 to 80	7— 9°	35—45°	48—36°
	over 80	6— 8°	45—50°	39—32°
Carbide tools	Free-machining	6—10°	70—90°	14— 0°
		6—10°	65—80°	19— 0°
Diamond tools		0— 7°	75—83°	10— 0°

Table 39. Continued from page 259.

		Notched-bar impact strength ft.-lbs.	Shear strength	
			Tons/sq. in.	1000 lb./ sq. in.
Pure Mg	soft	10	6.3	14
wrought	hard	3.5	7.0	16
Aviomag G9		5	8.9	20
C Mg-9 Al				
Aviomag K6		7	9.5	21
Mg-6Al				
Pure Al	soft	70	4.4	10
99.5 %	hard	22	7.6	17
Anticorodal	soft	50	5.7	13
Al-Si-Mg	heat-treated	11	15.9	36
Avional	soft	36	8.9	20
Al-Cu-Mg	heat-treated	22	15.9	36
Virgin Copper	soft	70	—	—
99.6 %	hard	15	—	—
Brass (extruded)		18	—	—
Mild steel		43	about 22.2	50

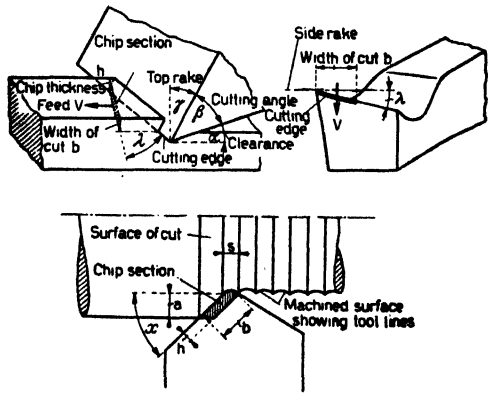
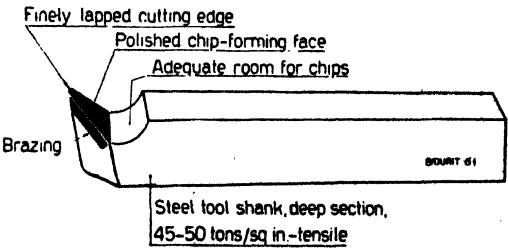


Fig. 319. Definition of machining terms.

Fig. 320. Carbide tipped (Bidurit) lathe tool (Vereinigte Drahtwerke A.G., Biel, Switzerland).



The smaller cutting pressure required for light alloys is no reason for using inferior tool materials, as the very high cutting speeds that can be used cause the tools to wear at an increased rate, which only the highest quality tools can stand up to. For this reason, too, hard metal carbide tools as shown in Fig. 320, are now much used for the machining of light alloys, especially for finishing cuts. For the highest class of finish, diamond tools are successfully used. With these latter tools, when taking light finishing cuts of not over 0.004 inch, speeds up to 15000 feet per minute can be used, giving a quality of finish even superior to lapping.

TABLE 41

RECOMMENDED COMPOSITIONS FOR TOOL STEELS (%)

	C	Mn	Si	Cr	W	V	Mo	Co
1	0.7	0.3	0.3	4.2	18	1.5	0.6	9.5
2	0.7			4.5	19	1.7	0.5	
3	0.8			4.5	14	2.1		

## c. Cutting force

The smaller resistance to severing of the light metals results in a smaller force being exerted by the tool in cutting (Fig. 321), and in consequence

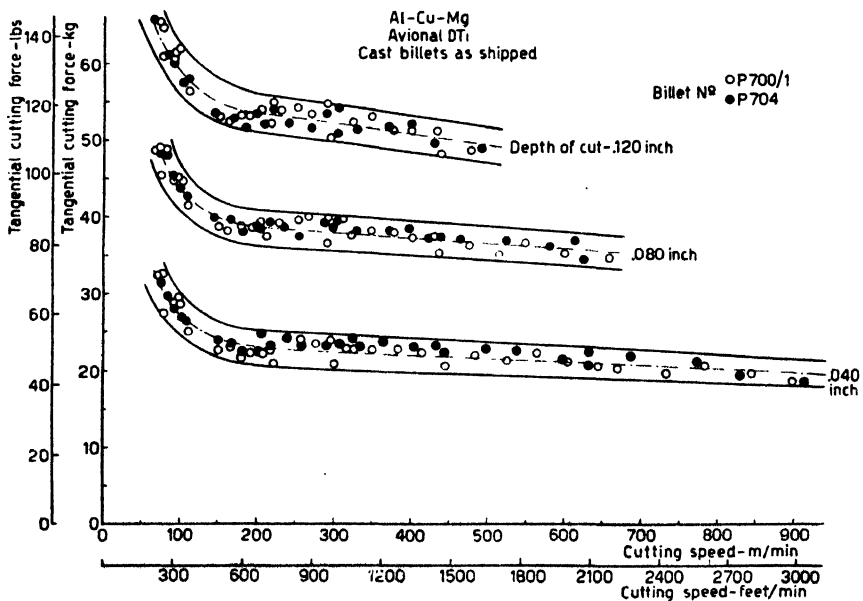


Fig. 321. Cutting force in machining Avional (Al-Cu-Mg, Duralumin), with various depths of cut and at various cutting speeds (von Burg).

a smaller power consumption by the machine. The illustration also shows how the cutting force diminishes with increased cutting speed. The biggest drop is obtained up to a speed of 600 feet per minute. A reduction in the cutting angle of the tool also leads to a reduction in the force of cutting but at the same time it leads to a more rapid rate of tool wear. Thus for the harder qualities of stock, a more obtuse cutting angle must be used on the tool, and a correspondingly lower cutting speed.

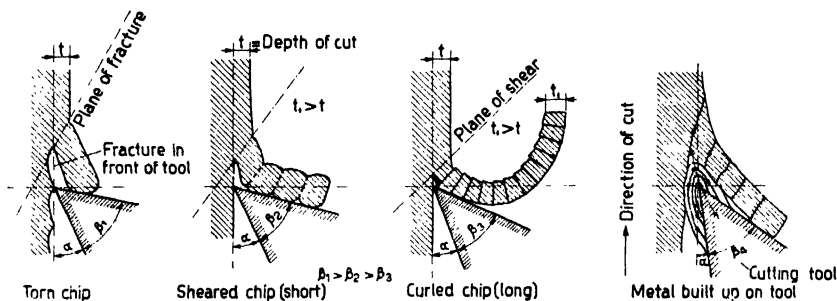


Fig. 322. Diagrammatic explanation of typical chip formation.

#### d. Shape of chip

The chips may come off the work in long curled chips, in short sheared chips, or in short torn chips. The last is caused by too great a feed, while short sheared chips come from special alloys or too great a cutting angle on the tool. A phenomenon in metal cutting is the formation of an accretion or built up edge on the tool (Fig. 322, right). This consists of particles of the stock piled up and stuck together and welded to the tool, which detach themselves when they get to a certain size, one portion leaving with the chip and another going on to the work, spoiling the machined surface. As the cutting speed increases, the formation of accretions ceases, usually at 900 to 1500 feet per minute, and the quality of the surface is then improved (Fig. 323). The effect of heat-treatment on the machining properties of light alloys is favourable, while the strong alloys always give better surfaces than the soft alloys.

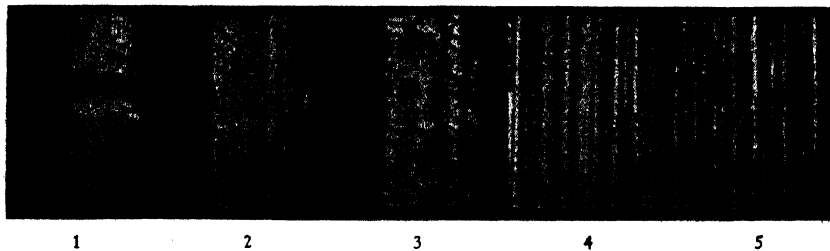


Fig. 323. Left: Effect of cutting speed on nature of machined surface (1, 2, 3). Right: Effect of heat-treatment (4, 5).

1: 2000 ft./min. 2: 1200 ft./min. 3: 350 ft./min. 4: Avional (Duralumin, Al-Cu-Mg) soft 5: Avional, heat-treated

e. *Chip formation*

To assist in reducing the power consumption, it is advisable that the chip removal should be as frictionless as possible. As the chip generally runs up the face of the tool, this must be very smooth and well rounded. With multiple teeth, as in saws and files, wide, open notches between the teeth must be provided, and these must be well rounded at the base. Chisel-cut teeth, as in files, should not be used as the chips are retained in the sharp recesses between the teeth and clog them. The smaller tool force is found to cause less generation of heat in the tool and chips. The temperatures of the tool for different materials at 300 feet per minute are 600 to 700°C (1112 to 1292°F) with steel, 210°C (410°F) for brass, 250°C (482°F) for Anticorodal (Al-Si-Mg alloy), 200°C (392°F) for magnesium alloys and 180°C (356°F) for pure aluminium. The tool temperatures increase with speed, and for Anticorodal at 900 feet per minute would be 375°C (707°F).

f. *Tool life*

The life index of a cutting tool can be defined as the time required for .004 inch of tool wear. This definition is too severe for roughing tools, in which a much greater amount of wear is permissible. In Table 42 are given the tool life indices in minutes for ordinary high speed steel tools, with a cutting speed of 2000 feet per minute, a clearance angle of 8°, a cutting angle of 45°, and a tool wear of .004 inch. The Table also gives the volume of metal removed in cubic inches per H.P. per minute. It can be seen from the Table that for strong alloys, the cutting angle of 45° is too small for the speed in question. With a greater cutting angle, or with a better quality of high speed steel, the tool life would be considerably greater.

TABLE 42

Alloy	Tool life index — minutes for .004 inch wear	Volume of metal removed cu. ins. per H.P. per min.
Pure aluminium . . . . .	20	5.5
Al-Mg7 and 9 . . . . .	10	
Mg-Mn . . . . .	6	
Al-Si-Mg solution heat- treated . . . . .	5	5.2
Al-Si-Mg solution heat- treated and warm aged .	4	4.9
Al-Mn . . . . .	3	
Al-Cu-Mg heat-treated . . .	3	3.7
Al-Cu-Mg annealed. . . . .	3	4.3
C: Al-Si castings . . . . .	2	



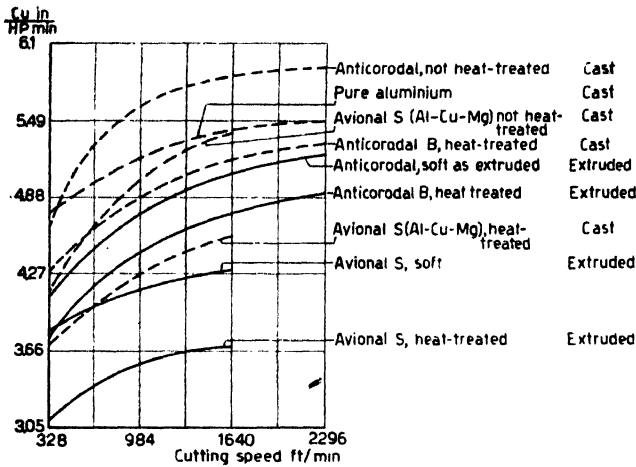


Fig. 324. Power consumption per cubic inch in machining of light alloys.

g. Rate of metal removal

While the tool life index for the various alloys varies over a considerable range, the volume of metal removed in cubic inches per horsepower per minute lies between 3 and 6 (Fig. 324). The best cutting conditions are obtained with the highest possible cutting speed and light feed. The recommended conditions, which vary somewhat with the types of operation, the tools and the materials, are set out in Table 43. When new machine tools are installed for use with light alloys, it is worth while to put in machines capable of

high speed and performance. In milling and sawing, the energy consumption increases with decreasing thickness of chip, slowly below .080 inch thick and quickly from .020 inch to .004 inch. The depth of cut or chip thickness should always be greater than .008 inch for economical machining, while on the other hand an

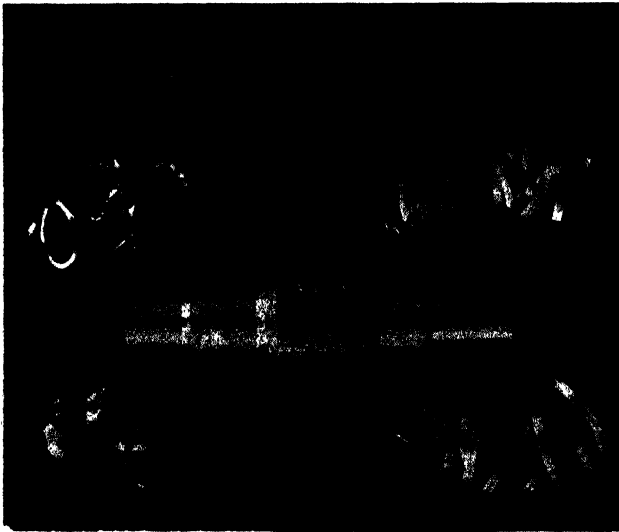


Fig. 325. Surface appearance with different cutting angles and lubrication.

Left: 75° cutting angle. Right 45° cutting angle. The outermost portions were lubricated

increase above .080 inch gives no advantage. Similarly the feed per tooth or blade should lie between .012 inch and .024 inch as far as possible.

#### *h. Cutting lubricant*

The low generation of heat in cutting and the high cutting speed in light metal machining results in a relatively low working temperature in the tools and of the work, as the greater portion of the heat is taken off in the chips. Except for sawing and drilling deep holes, extra cooling is not necessary. On the other hand, the surface quality is appreciably improved by use of a cutting lubricant as shown in Fig. 325. When a cutting lubricant is used, it is essential that this should have no corrosive effect on the chips, otherwise the swarf would lose value as scrap. Within this limitation, almost any lubricant in use for heavy metals can be used for light metals, such as sulphonated oils, mixtures of lard oil and paraffin, emulsified cutting oils, and even soap suds.

#### *i. Machining costs*

The machining properties of a material, i.e. the cutting pressure, the volume of metal removed per horsepower-hour and the rate of wear of cutting tools, should be taken into consideration in the choice of alloy for an application, as well as the strength and corrosion resistance that may be required, in cases where a substantial amount of machining enters into the manufacture of the article in question. Selection of a good machining alloy, especially of the Al-Mg or Al-Si-Mg types, can give considerable economies. The constitutional condition of the alloy, whether in the annealed, solution heat-treated, or fully heat-treated condition also has an appreciable effect on the machinability. As the high value of the metal is diminished if alloys of different composition are mixed, it is desirable to limit the different alloys in use to as small a number as possible and to ensure that the swarf from each alloy is carefully segregated for separate melting down.

Although it has been stated above that high cutting speeds are particularly advantageous, this does not imply that the older slower types of machine tools are of no use for the machining of light metals. It is certainly possible to do very good work with these older machine tools, though their efficiency is somewhat less than that of the latest high speed machines. Table 44 shows that the savings which may be achieved in the machining of light metals as compared with heavy metals are often sufficient to more than offset a higher material cost of the light metal.

TABLE 43  
BEST MACHINING CONDITIONS.

Operation	Type of tool	Max. cutting speed <sup>1</sup>			Max. feed (F) and depth of cut <sup>2</sup> ( $a_p$ ) - ins.					
		Pure Al.	Soft Alloys	Strong Alloys	Pure Al.		Soft Alloys		Strong Alloys	
					F	t	F	t	F	t
Turning					Feed in inches per revolution					
Roughing cuts	H. S. Steel	3000	2000	1300	.160	5/16	.120	1/4	.080	.160
Finishing "	H. S. Steel	4300	3000	2000	.040	.080	.028	.040	.020	.040
" "	Carbide tipped	7500	5500	3000	.020	.040	.020	.020	.020	.020
" "	Diamond	15000	9000	6000	.008	.004	.004	.004	.004	.004
Milling					Feed in inches per blade					
Roughing cuts	H. S. Steel	3700	2300	1600	.008	5/16	.006	1/4	.004	.160
Finishing "	H. S. Steel	5000	3600	2400	.004	.080	.002	.040	.001	.040
" "	Carbide tipped	7500	5500	3000	.080	.004	.040	.004	.004	.004
Circular sawing	H. S. Steel	7500	4500	1800	Feed in inches per tooth for 1 1/8" thick stock					
" "	Carbide tipped	6000	4500	3000						
Band sawing	H. S. Steel	6000	4500	3000						
Boring	H. S. Steel	300	150	75	Feed in inches per revolution					
Reaming	H. S. Steel	180	120	60						
Screw cutting	H. S. Steel	120	90	60						
Drilling:					Feed per revolution for hole diameters as below — inches					
Depth of hole										
5D	H. S. Steel	1300	900	600						
10D	without	600	300	250						
20D	jig	300	150	125						
5D	With jig	600	450	300	.004	.008	.012	.016	.020	

<sup>1</sup> ft./min.<sup>2</sup> or Thickness of chip.

TABLE 44  
MACHINING COSTS OF A MOTOR CRANKCASE

	Aluminium alloy casting machined on special machine tools	Cast iron machined on ordinary machine tools
Weight—lbs . . . . .	88	240
Cost of rough casting, say . . . . .	160 shillings	55 shillings
Machine tools employed . . . . .	2	3
Machine hours occupied . . . . .	40	70
Wages cost, say . . . . .	100 shillings	176 shillings
Overheads . . . . .	250% 250 shillings	350% 616 shillings
Total cost . . . . .	510 shillings	847 shillings

In this case the part was a motorcar crank case. The lower proportion of overhead charges for light alloy follows from the use of higher speed machine tools, the number required being reduced from 3 to 2 with one operator per machine in each case, so that there is a lower direct wages charge as well as a smaller capital value of plant.

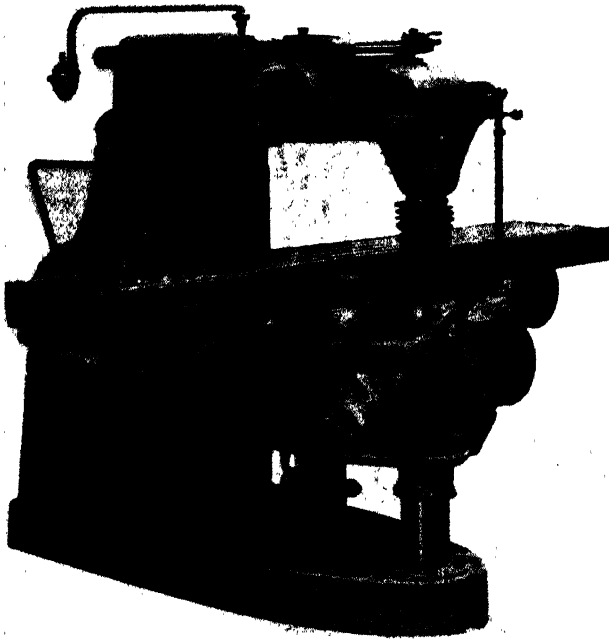


Fig. 326. Universal milling machine (Starrfräsmaschinen A.G., Rorschach, Switzerland).

k. *Work holding means*

To obtain the best results from the special high speed machine tools, it is necessary to reduce to a minimum the idle time absorbed in removing a finished piece of work and setting up a new piece. In Fig. 326 is shown a milling machine with a long table, on which, while one piece of work is being actually machined at one end of the table, a finished piece may be replaced by a new piece at the other end, so that the idle time is only that required for a quick traverse of the table to bring the new piece up to the cutter as soon as the old one has been finished. The high cutting speed usually causes the chips to fly about, which may be a source of danger to the operator, so that a swarf collection attachment is advantageous.

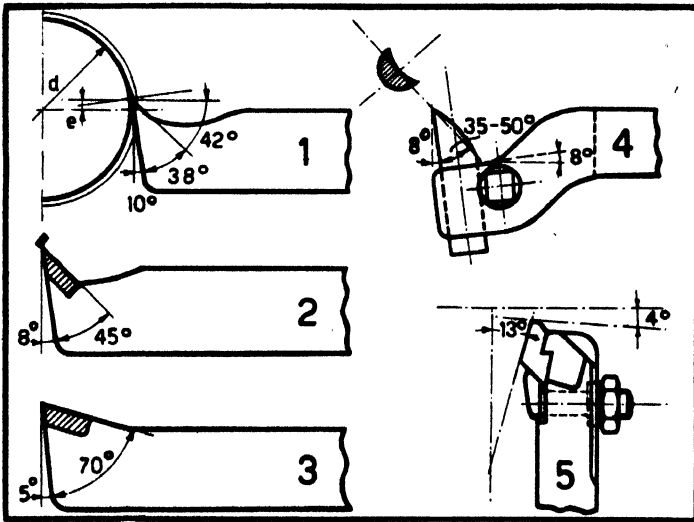


Fig. 327. Turning tools.

- |  |                 |
|--|-----------------|
| 1. Tool for pure aluminium                 | 4. Tool holder  |
| 2. Tool with carbide tip for pure Al       | 5. Ifanger tool |
| 3. Carbide tipped tool for Silumin (Al-Si) |                 |

## 2. TURNING

Steel lathe cutting tool shapes are shown in Fig. 327. To avoid forging the high speed steel to shape, it is advisable to use tool holders with tool bits that only need grinding to shape. It is recommended to use special tool grinding machines in order to obtain the required angles accurately. The high cutting speed and the formation of the chips give rise to rapidly

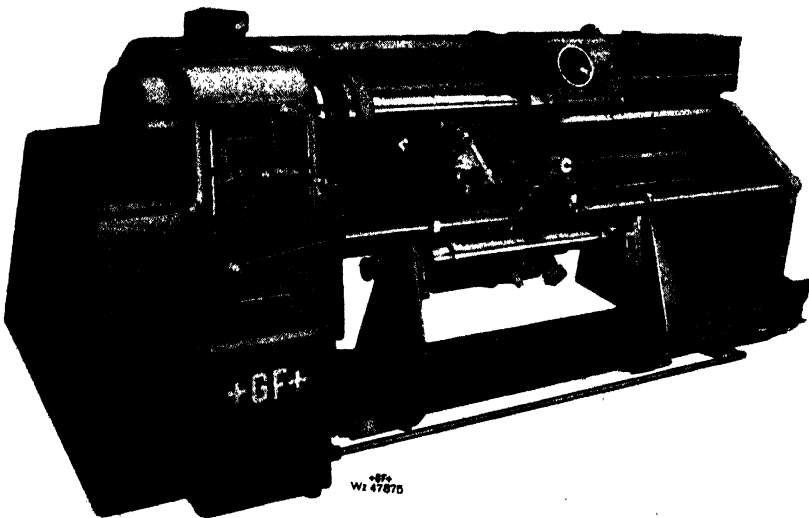


Fig. 328.

+ GF + Copying lathe, type KQM (George Fischer Ltd., Schaffhausen, Switzerland).

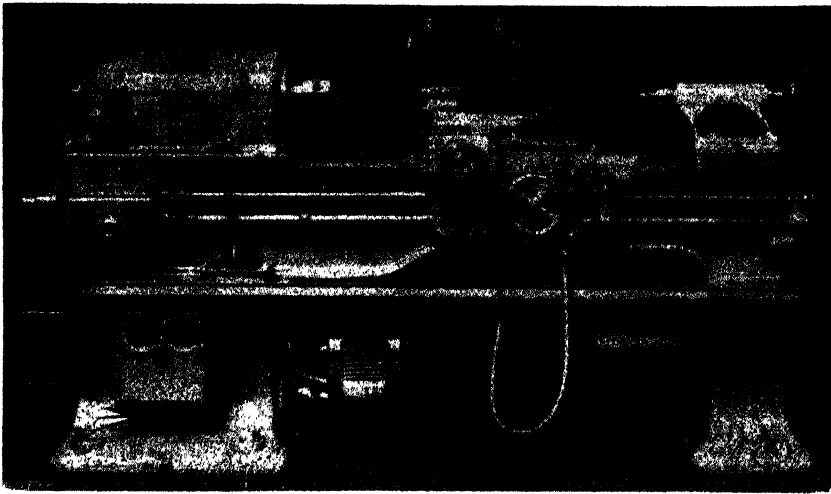


Fig. 329. Special lathe for light metals (Cazeneuve).

fluctuating loads on the tool and may cause this to chatter. Very robust tools and tool holders should be used, and these should be as short as possible. Swarf collection should be arranged for. Fig. 328 shows a good type of copying centre lathe of rigid design with the tool held below the work and directed vertically, which is very suitable for the turning of light metals. Unrestricted swarf removal is assured by the special design of the lathe bed, the chips being delivered straight into a box on wheels placed behind the lathe. A brake is provided to bring the high speed spindle quickly to a stop, and pre-selected speed control is preferable to facilitate changes of speed. It is obvious that a smooth rotation at high speeds is only obtainable with a robust design and perfect bearings. Fig. 329 shows a standard lathe specially designed for light metal turning with extra high spindle speeds.

In heavy duty lathes, a hydraulic oil traverse for the saddle is sometimes provided instead of the usual lead-screw traverse. The former has the advantage that the feed adapts itself to the depth of the cut, giving a uniform thrust so that the lathe always works under the best condition of cutting pressure.

Special tools are used for the cutting of curved shapes from sheets, which may be either a rapidly reciprocating percussive chisel or "nibbler" (Fig. 330), or a single bladed milling cutter or router as in Fig. 331. These tools are frequently worked with a copying attachment, a pack of sheets being cut out at one operation.



Fig. 330.  
Nibbling machine with punching tool  
(W. Maurer, Schaffhausen, Switzerland).

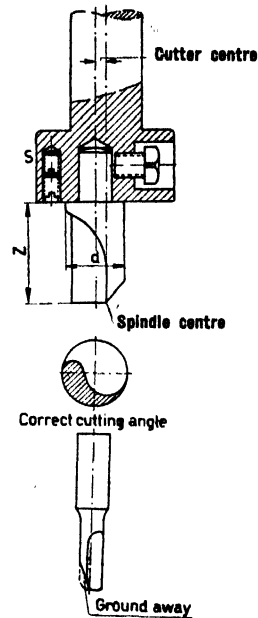


Fig. 331. Routing tool.

### 3. MULTIPLE-TOOTHED CUTTING TOOLS

In the operations of sawing, filing, milling, drilling, and tapping, the cutting tools have a plurality of cutting edges. The clearance of the chips from the teeth is a special problem with multiple teeth, calling for broad, open notches between the teeth, each with a smooth well radiused bottom. A relatively large pitch of the teeth is generally adopted to permit this, and in the case of saws and files, these should not be punched or chisel cut, as light metal chips clog such notches. It is found by experience that the smallest depth of cut for clean cutting is 0.002 inch and, with a given number of cutting edges and a given cutting speed, a certain minimum feed must be maintained, otherwise the cutter slips over the work and merely grinds it off rather than severs the chips properly.

#### a. Sawing

Strongly built bandsaws and circular saws with high speeds cutting up to 13000 feet per minute are the best types of machine for the sawing of light metals. Fig. 332 shows the best shape of tooth for bandsaws, and this is also applicable to circular saws and milled files. The best material for saw blades is a naturally hard or self hardening steel. For circular saws operating on strong alloys and hyper-eutectic Al-Si alloys, carbide

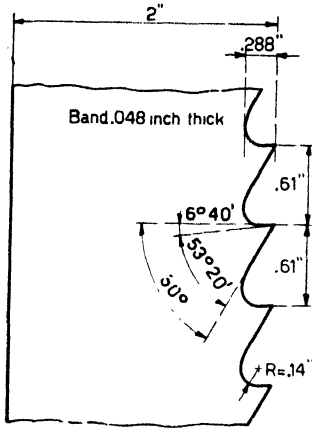


Fig. 332.  
Development of band saw.

tooth inserts are recommended, and the speed must then be kept below 3000 feet per minute. To withstand the high speeds of band and circular saws, the bearings must be adequate for their duty in order that quiet running and a clean cut may be obtained.

Fig. 332a shows a heavy circular saw for the sawing up of continuous-cast rolling blocks of  $40 \times 8$  inches cross section. The saw blade is 50 inches diameter and .362 inch thick, with a peripheral speed of 9000 feet per min. With a power consumption of 150 H.P., the linear speed of cutting is 15 feet per min., which requires cooling of the saw blade with a 4% soluble oil solution.

#### b. Filing

As shown in Fig. 333, double cut chip-breaking teeth may be utilised. These divide the filings into short lengths, making them less liable to clog the teeth, and requiring less effort for the filing. In hand filing, the correct application of the file counts greatly in obtaining the best surface.

#### c. Milling

In milling with cylindrical cutters, the same principles apply as for circular saws. For smooth cutting, at least two teeth of the cutter should be in engagement with the work at one time. Owing to the large pitch of the teeth often found in

ordinary milling cutters, this is not always possible, and chatter may then take place. Special milling cutters are therefore used for the milling of light metals, as in Fig. 334, with the helical teeth with a helix angle of  $30^\circ$  from the axis. This not only gives the advantage that several teeth may be in

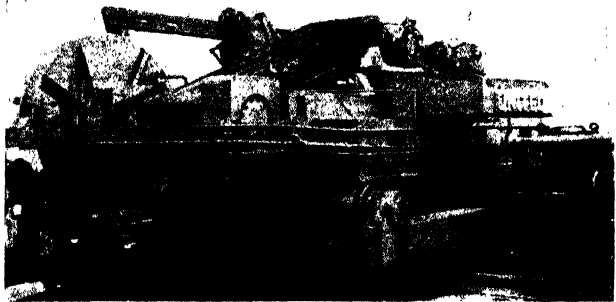


Fig. 332a. Heavy circular saw for sawing rolling blocks  
(United Engineering and Foundry Co., Pittsburg.).



engagement at once, but they throw the millings out to one side. To eliminate axial thrust, large milling cutters may be made of the double helical type, as in the illustration, so that the end thrusts of the opposite halves counterbalance one another.

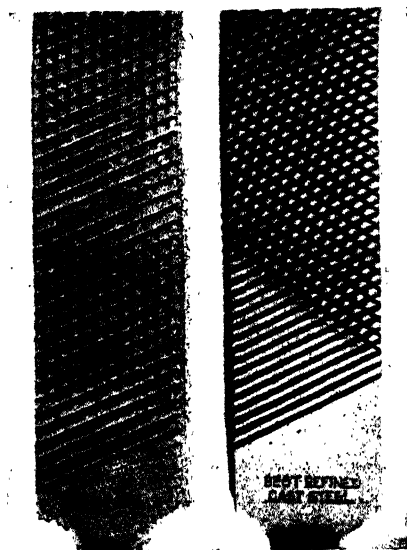


Fig. 333. Special files for light metal.  
Left: Beiter. Right: Osborn.



Fig. 334. Double helical milling cutter for light metal.

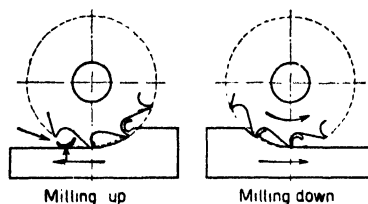


Fig. 335.

Left: Up-milling (opposite directions).  
Right: Down-milling (same directions).

In the machining of heavy metal, as shown in Fig. 335, the direction of rotation of the cutter is almost always opposite to the travel,<sup>1</sup> but to mill light metals with the feed in the same direction as the cutter is revolving,<sup>2</sup> especially in roughing cuts, results in a lower rate of tool wear. If on the other hand, a casting with a hard skin is being milled, it is preferable that the milling cutter should run in the opposite direction to the traverse<sup>1</sup> for roughing, so that the cutters do not bite on to the cast skin but remove this from below. The opposite opinion, that the milling cutter running in the same direction as the travel<sup>2</sup> results in a lower surface finish, is not found to be so in the case of light metals with correct machining practice.

For the machining of flat surfaces, good results are obtained with a plano-miller, with single cutting blades set in a flat cutter head. A smaller number of blades is used than for the plano-milling of the heavy metals, this ranging from 2 to 14 according to cutting speed, feed, type of material and size of cutter head. Fig. 336 shows the most suitable tool shapes.

<sup>1</sup> Conventional or up-milling.

<sup>2</sup> Down-milling.

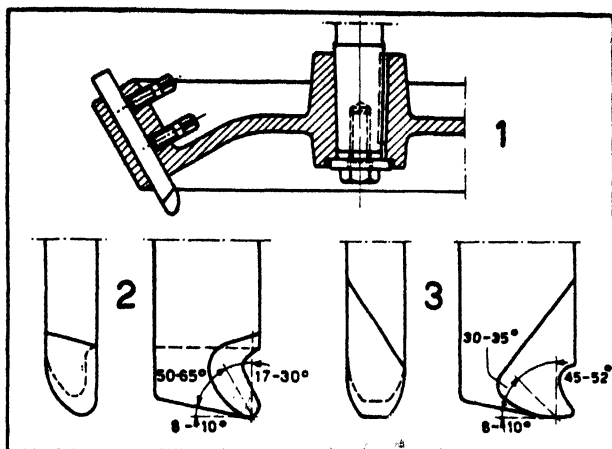


Fig. 336.  
Blades for plano-miller.

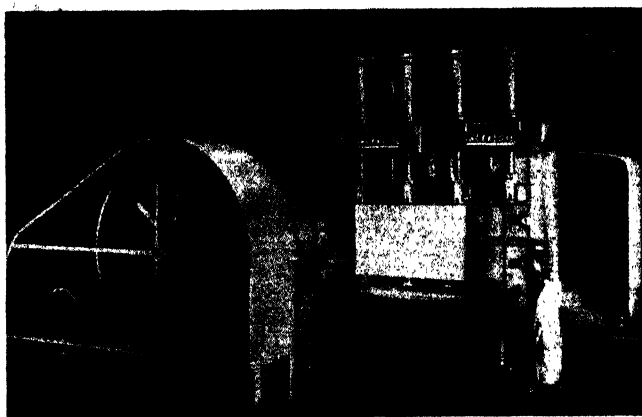


Fig. 336a. Ingersoll  
block scalping  
machine for scalping  
large aluminium  
rolling blocks.

If a very smooth finish is not important, the operation may be completed in one cut using a cutter head having two rings of tools on different pitch circles, i.e., roughers and finishers. Fig. 336a shows a block scalping machine with a cutter head 50 inches diameter, running at a peripheral cutting speed of 2800 feet/min. with a feed of 9 ft/min. The power consumption is 430 H.P. The cutter head had 40 inserted tools, spaced 4 inches apart. With cylindrical milling cutters, it is not always possible to achieve the desirable high cutting speeds owing to the small diameter of the cutter, but with plano cutting heads, any desired cutting speed up to 5700 feet per minute can be obtained. Fig. 337 shows a copying milling machine with cutter heads for the simultaneous milling of two propeller blades in light alloy, using a cutting speed of 4500 feet per minute with

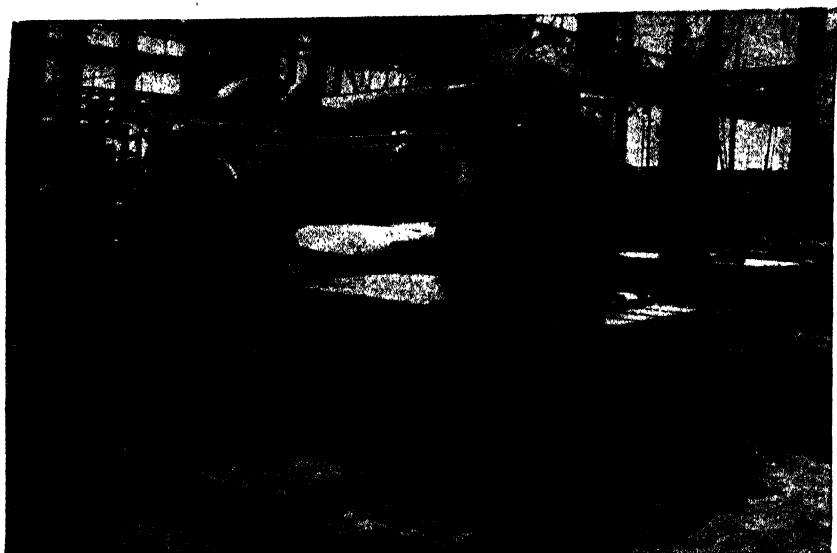


Fig. 337. Copying miller for propeller blades  
(Escher-Wyss Maschinenfabriken A.G., Zurich, Switzerland).

a feed range of .040 to 1.5 inches per minute. Depths of cut up to 1.5 inch and a work revolution speed of  $1\frac{1}{2}$  to 8 revs. per minute can be used.

#### d. Drilling

Special twist drills are required for drilling holes of substantial depth. These should preferably have an angle of twist of the flutes of  $40^\circ$  and a point angle of  $140^\circ$ . The greater twist of the flutes compared with the standard drills for steel ensures a better clearance of the drillings from

the flutes. The best practice is to use special drilling machines built to work at the highest possible revs. per min. For instance for holes up to  $\frac{3}{8}$  inch diameter, 10000 to 15000 r.p.m. are used. The power consumption in the drilling of light metals is only about  $\frac{1}{3}$  of that for mild steel. Fig. 338 shows various bits

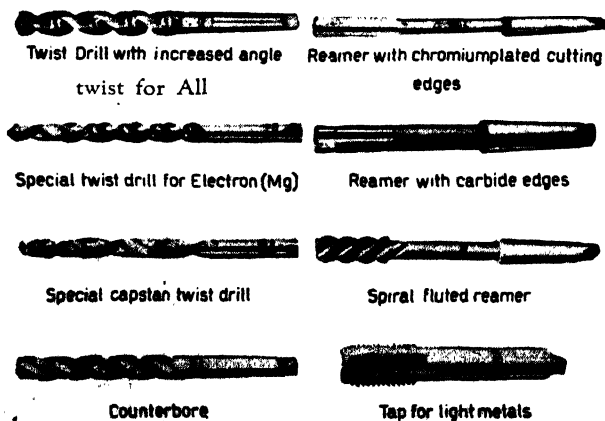


Fig. 338. Drills, reamers and taps for light metals.

for use in the drilling machine, including twist drills, reamers, and taps. It is found in practice that twist drills always make a hole slightly bigger than themselves. The amount of oversize depends on the nature of the material and the drill speed. When holes of accurate size and circularity are required, they should be drilled under size and reamed to size. In drilling, the same lubricant is used as for sawing and milling. For reamers, a 5 to 4 petrol-turpentine mixture gives the most accurate dimensions, but also brings a risk of seizure of the reamer. It is in most cases better to use a light oil with reamers, with which the oversize of the holes over the reamer is .002 to .005 inch according to the alloy, the smallest oversize coming with the hardest alloys.

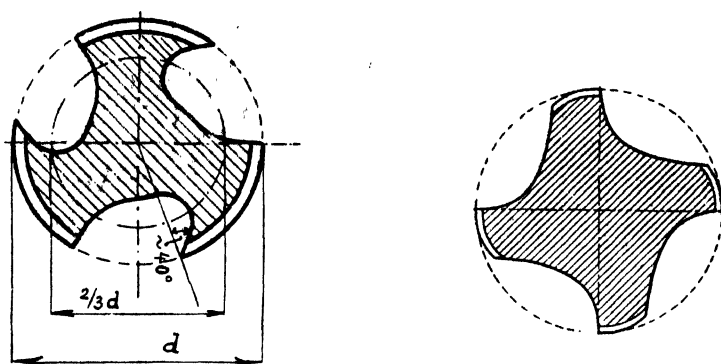


Fig. 339a. Cross-sections of taps, left for light metals, right for heavy metals.

#### e. Tapping

In the case of tapping also, special taps give the best results. These are shown in Fig. 339a. In general three-fluted taps are used with radial back faces not ground for backing. This is necessary for blind holes from which the tap is screwed out backwards. If ordinary engineers' taps, as used for heavy metals, are used for light metals, there is a danger that swarf might be pressed in the screw threads, thus tending to spoil them. On account of the lower hardness of the light metals, it is usual to use coarser threads with rounded roots. For screws which must be unscrewed frequently in use, bolts going right through, with washers  $2\frac{1}{2}$  times the hole diameter, should be used. If this is not possible, screw-holes should be bushed with heavy metal. The bushes may be either cast or screwed in, in which latter case they should be first painted with zinc white paint, which when dry will hold the bush tightly in the aluminium. Tapped holes in light metals should always have a depth of  $2\frac{1}{2}$  times the diameter.

As referred to in Chapter XII, p. 232, use is made of rubber tools in the

forming of light metals. These are also of use in the punching out of shapes from sheet stock. For this the die is cut out of steel plate exact to the shape required and with sharp edges. This is mounted on a level press plate. The sheet metal stock to be punched is placed upon it, and the rubber punch is brought down on it with the necessary pressure. By this means the sheet is punched out exact to the shape of the hole in the steel plate. (see Fig. 339b).

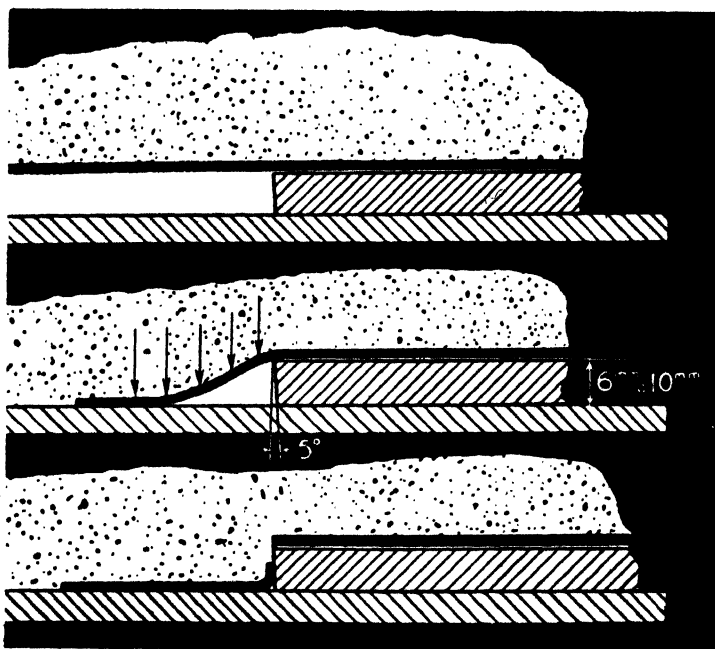


Fig. 339b. Rubber tool for punching sheets .028 inch thick.

## CHAPTER XV: SOLDERING AND WELDING

### 1. GENERAL

The main difficulty in joining the light metals by welding and soldering arises from the tenacious and refractory surface oxide film. Sound fused joints cannot be made without removing this. The problem is either to find a flux to remove the oxide film at the welding or soldering temperatures, or to remove it mechanically, and so to bring about a metallic union between the light metal and a suitable solder. Both processes have been in use since the early years of the present century, and the following various methods of joining aluminium are now in use :

Reaction soldering	Electric arc welding
Soft soldering	a. Atomic arc welding
Hard soldering or brazing	b. Gas-shielded arc welding
Hammer welding	c. Ordinary arc welding
Autogenous or gas welding	Resistance welding
Aluminothermic welding ("Alutherm")	a. Seam welding
	b. Butt welding
	c. Spot welding

### 2. REACTION SOLDERING

The essential soldering medium is a paste of tin chloride in paraffin oil. This is spread on the surfaces to be joined which are placed together and heated by a gas flame or electric hot plate to  $230^{\circ}\text{C}$  ( $446^{\circ}\text{F}$ ). At this temperature the aluminium replaces tin in the chloride compound and the aluminium chloride is vaporised, removing at once the aluminium oxide, so that the liberated metallic tin can form a metallic union with the aluminium. To make a stronger joint, the tin joint may be afterwards reinforced with ordinary soft solder. This method is particularly suitable for the mass production of small articles which may be heated in a muffle furnace for the soldering operation.

## 3. SOFT SOLDERING

For soft soldering, the use of a flux is often omitted and the oxide film is removed mechanically from beneath the molten solder by means of a wire brush or scraper.

TABLE 45

## TYPICAL SOFT SOLDERS FOR ALUMINIUM

Solder:	Composition .... %						Melting point or melting range.	
	Al	Zn	Sn	Cd	Pb	Cu	°C	°F
Pure Zinc . . . . .	—	100	—	—	—	—	420	788
96 Zn . . . . .	4	96	—	—	—	—	380	716
80 Cd . . . . .	—	17.5	—	82.5	—	—	265	509
50 Sn . . . . .	—	48	48	—	1.5	2.5	200	392
90 Sn . . . . .	—	8	90.5	—	1.5	—	to 350 200	to 662 392

Table 45 gives the compositions of some typical soft solders. A soldering temperature of 250° to 400°C (482° to 752°F), according to the particular solder, is sufficient. The 90Sn solder is non-poisonous and may thus be used for vessels used in connection with foodstuffs. In the case of solders melting below 300° (572°F), a soldering iron can be used, to which a small wire brush may be fixed, (Swiss patents 152953; 157259, A. ULRICH) to brush aside the oxide film with the movement of the soldering iron. With the higher melting solders, a blow pipe flame is used, as for hard soldering, and a flux is then used, of which examples are given in Table 46.

TABLE 46

## FLUXES FOR SOFT SOLDERING

Name of Flux	Melting point		Applications
	°C	°F	
Lumisold M . . .	about 350	662	Normal hard and soft soldering flux powder for Al and Al alloys <sup>1</sup>
Lumisold T . . .	about 200	392	Reaction soldering paste with low reacting temperature for Al and Al alloys <sup>1</sup>
Lumisold K . . .	about 350	662	Special soldering paste for cables <sup>2</sup>

<sup>1</sup> The flux which remains on the joint is hygroscopic and must be completely removed by a thorough washing after the operation.

<sup>2</sup> The flux residue is completely driven off after sufficiently prolonged heating.

One important application of soft soldering is in the repair of aluminium castings. For this, the surfaces of the casting to be soldered are thoroughly cleaned and heated up to 300 to 400°C (572 to 752°F), then first tinned with a high-tin solder by the rubbing method. Then the joint or cavity is filled with a plastic wiping or modelling solder having a large melting range. When small pieces are broken away from a casting, these may be entirely built up afresh with this type of solder. The composition of such a modelling solder may be for example Zn 39%, Sn—39%, Al—20%, Pb—1%, Cu—1%.

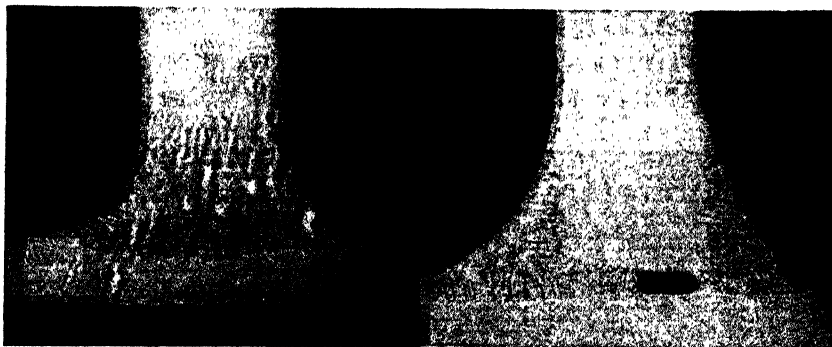


Fig. 340. Hard-soldered joint after 12 months exposure to corrosive conditions.

#### 4. HARD SOLDERING OR BRAZING

Hard soldering or brazing, as it is also called, is employed in somewhat similar cases to welding, which is described later, and the melting points of the solders used, as given below, are not greatly below the melting point of aluminium. The electrochemical solution potentials of the soft solders are generally much different from that of the underlying metal; the solution potentials of hard solders, on the other hand, are much closer to that of the material being joined. Thus hard solders of this type have a high degree of permanence under corrosive conditions. Fig. 340 shows such a brazed joint after a 12-month exposure to a salt-spray corrosion test.

TABLE 47  
COMPOSITIONS OF HARD SOLDERS

Solder	Constituents %			Melting point or melting range	
	Al	Si	Zn	°C	°F
4 Si	96	4	—	575—630	1067—1166
13 Si	87	13	—	575	1067
10 Zn	90	—	10	600—650	1112—1202
50 Zn	50	—	50	475—575	887—1067



The first three hard solders are non-poisonous and therefore are suitable for the brazing of vessels used in handling foodstuffs.

The practice of furnace brazing has been developed in recent years. It has been found advantageous to use pure aluminium sheet clad with Al-Si alloy with 5 to 12% Si for processing by this method. As the metal of the coating melts at  $550^{\circ}\text{C}$  ( $1022^{\circ}\text{F}$ ) and the core metal melts at  $650^{\circ}\text{C}$  ( $1202^{\circ}\text{F}$ ), it is possible by heating assemblies of this material to  $575^{\circ}\text{C}$  ( $1067^{\circ}\text{F}$ ) to obtain sound welded joints simply, if the places to be joined are painted beforehand with flux. Fig. 341 shows an assembly brazed in this manner. The best procedure is to immerse the assembly in a bath of molten flux. By so doing, heating is most rapid and the correct brazing temperature can be most accurately attained. An immersion for one minute in the flux bath is usually sufficient.

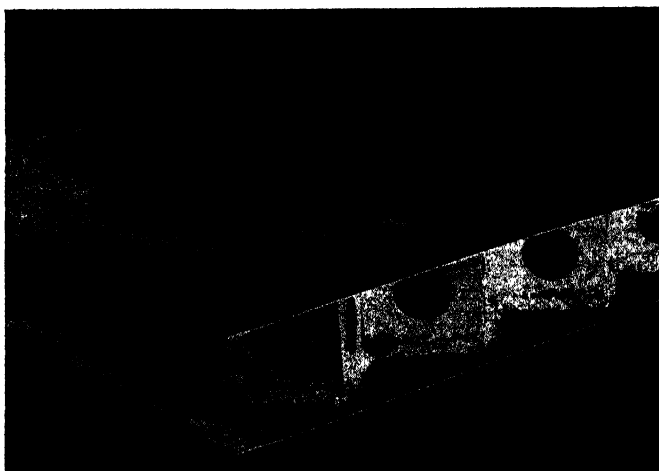


Fig. 341. A furnace-brazed assembly.

## 5. HAMMER WELDING

Aluminium can be joined by hammer welding in a somewhat similar fashion to iron. For this, the temperature must be raised to between  $550^{\circ}\text{C}$  and  $600^{\circ}\text{C}$  ( $1022^{\circ}$  to  $1112^{\circ}\text{F}$ ), and no flux is used. The oxide film is broken by the deformation of the weld under the hammer, and metallic union takes place in between the broken patches of oxide. As hammer welding requires great skill and can only be done where it is possible to use a suitable support, it is not much used in practice, and autogenous welding is generally used instead.

A recent variation of hammer welding is the pressure welding method developed by the Junkers aircraft firm. In this method, the sheet parts are

pressed together at the joint by heated pressure faces ( $550\text{--}600^{\circ}\text{C} = 1022\text{--}1112^{\circ}\text{F}$ ) to cause a reduction of thickness of about 50%, which allows the contacting surfaces to weld together. This process is suitable for pure aluminium and the softer alloys such as Anticorodal (Al-Si-Mg). Particular attention is required for the treatment of the pressure faces, in order that the aluminium shall not adhere to them. They are made of a hot die steel, ground to a certain degree of roughness. Before use, they are painted with a talc-saltpetre mixture and are heated to the working temperature. In spite of this, the first sheets may stick. These are also painted with a 2 to 1 talc-saltpetre mixture and as often as necessary are torn away from the pressure faces, until an aluminium oxide coating has formed on these, which will prevent further adhesion.

The welding pressure is 2 to 5 tons/sq. in. (4500—11000 lb/sq. in.) and the time of welding is only about 10—30 seconds. Thus, allowing for the preparation of the material, a weld can be made in about 30—45 seconds. One set of tools may last for the welding up to 750,000 radiator elements.

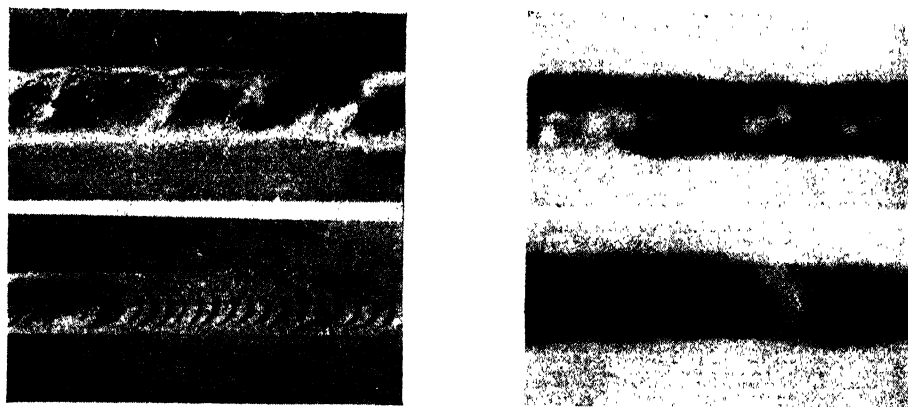


Fig. 342. Autogenous welded joint.

Below : With flux. Above : Without flux. Left : Surface appearance. Right : Radiographs.

## 6. AUTOGENOUS WELDING

Autogenous, oxy-acetylene or gas welding, the method most widely in use, was brought out almost simultaneously by ODAM in Paris and M. U. SCHOOP in Zürich.

### a. *Welding flux*

If two aluminium sheets are joined by simple fusion welding, a rough joint is obtained, as shown in Fig. 342 (upper pictures), which is broken up by the tough oxide skin of the metal, and which is also seen in the radiograph to give rise to numerous defective places. When, however, a flux is used, capable of dissolving the oxide, a good metallic joint is

obtained which is also sound under X-rays, as shown in the lower illustrations of Fig. 342.

Schoop recognised the true importance of the flux and took out the basic patent in 1907 on a flux for welding aluminium consisting of a mixture of alkali halides (Swiss Patent 41457). After the patent had expired, many brands of aluminium welding flux appeared, which in general approximated to the following composition:

NaCl, 28—32%	LiCl, 20—30%
KCl, 24—30%	NaF, 10—20%

The requirements of a good aluminium welding flux are several. In the first place it must have a high solvent power for aluminium oxide. Secondly it must have a melting point below that of the material to be welded. It must possess a slightly viscid fluidity in order not to spread too widely over the work, and to adhere satisfactorily to the welding rod, and it must have a low specific gravity. Most welding fluxes are hygroscopic and must therefore be kept in tightly closed containers, as they deteriorate if they become damp. They should therefore be mixed with soft water (rain water) only a short time before use. As metal containers would be attacked, the above mixture should be kept in glass, earthenware or wood containers. It is best practice to mix the flux to the consistency of a thick soup. The flux is strongly corrosive to aluminium and should therefore not be allowed to remain for long in contact with it. The welding or filler rod is coated with the flux shortly before use. In difficult jobs, the joint is also painted with the flux paste on both sides. Unused welding rods should be washed clean, and the welded joints, after completion of welding and cooling down, must be very carefully cleaned. To be perfectly safe, a dip in 5 to 10% nitric acid should then be given and finally another rinse in water.









As the flux partly volatilises in the welding operation, and condenses again on the surrounding surfaces, welding should be carried on in a closed, well ventilated shop. Finished and cleaned work should be immediately taken out of the welding shop so that it is not again contaminated with the flux vapour.

#### b. Filler rods

The basic principle of autogenous welding is that the filler material shall be of the same composition as the work itself. With alloy work this condition is somewhat modified, but in such cases the filler material should have the same electrochemical solution potential as the material of the work, as this is necessary to avoid any risk of corrosion. When the weld is correctly made, it will have the same high resistance to cor-

TABLE 48

FILLER RODS FOR AUTOGENOUS WELDING: LENGTH 32 INCHES; DIAMETER 0.080, 0.120, 0.200 AND 5/16 INCH

Filler material	Symbol	Shape and marking of rod	Use	Tensile strength for weld on 1/8 inch thick sheet			
				Not welded		Welded	
				Tons/sq. in.	1000 lb./sq. in.	Tons/sq. in.	1000 lb./sq. in.
99.5% Aluminium	Al	Round Smooth 	Pure Al	5—11	11—24	5—6	11—13
			Aluman (Al-Mn) BA60, 3S	6—14	13—31	6—8	13—18
Raffinal (Super purity aluminium)	Raf (SP)	Round Notched 	Raffinal (SP) Reflectal (Brytal)	2.5—10	5—22	2.5—3	5—7
			Pure Al	5—11	11—24	2.5—5	5—11
Al + 4% Si	4 Si	Square Smooth 	Anticorodal type (Al-Si-Mg BA24, 51S, etc. (not heat-treated after welding)	6—25	13—56	6—11	13—24
			Various wrought alloys.	—	—	—	—
Anticorodal type (BA.24 etc.) (Al-Si-Mg)	Ac	Square Notched 	Anticorodal type, as above heat-treated after welding (cast and wrought)	6—25	13—56	20—24	45—54
Peraluman 3 (Al-3Mg)	Pe-3	Hexagonal Smooth 	Peraluman 1, BA20, 4S	10—19	22—43	10—14	22—31
			Peralumin 3, BA21, 52S, Birmabright (cast and wrought)	14—20	31—45	14—15	31—34
Peraluman 7 (Al-7Mg) (MG7)	Pe-7	Hexagonal Notched 	Peraluman 5, (cast and wrought)	17—25	38—56	17—19	38—43
			Peralumin 7, MG7 (cast and wrought)	19—25	43—56	19—22	43—49
Avional (Duralumin) (Al-Cu-Mg)	Av	Triangular Smooth 	Avional (Duralumin)	10—32	22—72	24—28	54—63*
			Al-Cu casting Alloys	—	—	—	—
Al + 13% Si	13 Si	Triangular Notched 	Silumin (Al-13Si), Alpax, Wilmil, BA40D	—	—	—	—
			Various casting alloys	—	—	—	—

\* heat-treated after welding.

rosion as the rest of the work. In the case of heat-treated alloys it is to be remembered that the heating of the weld will cause an extension of the ageing process along the joint, whereby strength and corrosion resistance are adversely affected. Should no further heat-treatment be possible after welding, the region of the weld may have a lower strength and corrosion resistance than the rest. The choice of filler material depends on whether the alloy is to be heat-treated after welding or not. Table 48 shows the types of filler rod that are used in Switzerland, and their designations. In order that they should not be confused in use, the welding rods of the different groups are made in characteristic shapes, which also facilitates the identification of the scrap ends of the rods.

### c. Welding blowpipes

The technique of the oxy-acetylene welding of aluminium is similar to that of iron. Similar sizes of welding torch or blowpipe are used, although

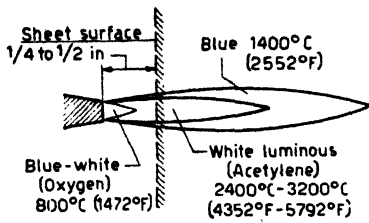


Fig. 343. Acetylene welding flame.

making of a three feet length of welded joint. The blowpipe flame is adjusted so that there is a slight excess of acetylene, as shown in Fig. 343, the white cone then being an inch or two in length.

beginners with aluminium will find it better to use a tip or nozzle one size smaller than for steel. For plate over 3/8 inch thick, it is better to use a size larger than for steel. Table 49 shows the best diameter of tip and the consumptions of acetylene gas for different sheet thicknesses, while Table 50 gives some details pertaining to the

TABLE 49

NOZZLE OR TIP SIZES AND ACETYLENE CONSUMPTION IN THE OXY-ACETYLENE WELDING OF ALUMINIUM

Tip No.	Diameter of orifice, inch.	Acetylene consumption cu. ft per hr.	Thickness of material, inches
00	.032	2—3½	.020—.040
0	.040	3½—7	.040—.080
1	.048	7—14	.080—.160
2	.056	14—25	.160—½
3	.072	25—40	½—¾
4	.088	40—70	¾—1
5	.104	70—100	1—1½
6	.120	100—180	1½—2

d. *Welding procedure*

The physical properties of aluminium call for the adoption of a special technique in oxy-acetylene welding. The high coefficient of expansion and high solidification shrinkage of the metal as well as its low hot-strength call for much skill on the part of the operator. The rather low melting

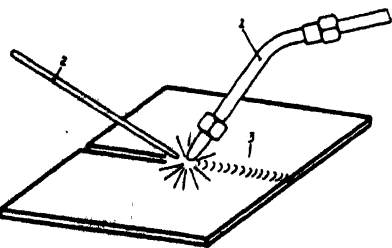


Fig. 344. Application of the blow-pipe in oxy-acetylene welding.

point on the one hand and the high heat-conductivity on the other necessitate a very hot flame and speedy working, so that an excessive distortion of the work does not take place. The tip of the blowpipe is held fairly steeply to the work, as in figure 344, while the filler rod is held rather flat in the left hand which is protected by an asbestos glove. Welding is

usually carried out from right to left, and the filler rod does not remain in the flame all the time, but about twice a second is dipped in the pool

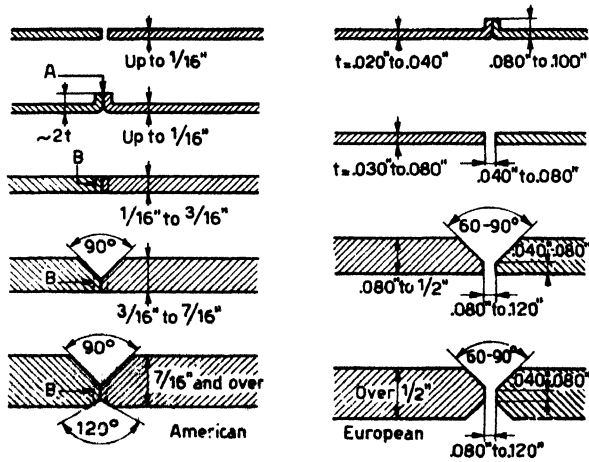


Fig. 345. Preparation of acetylene welded joints.

of the weld and is then immediately withdrawn from the flame. In view of the high thermal conductivity of aluminium, it is advisable to preheat the line of the joint to 300–400°C (572–752°F) before welding. For difficult jobs, the whole piece may be preheated in a furnace to this temperature.

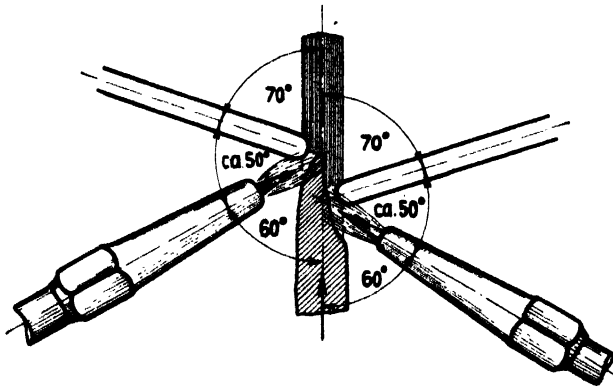


Fig. 346. Application of blowpipes in welding from both sides.

As shown in Fig. 345, the edges of the plates to be joined, if 1/8 inch thick or more, are bevelled. Sufficient filler metal should be laid on so that the bead stands slightly proud on both sides of the plate. In welded jobs over 5/8 inch thick, welding is often done on both sides simultaneously as in Fig. 346. This calls for considerable operating skill.

The parts to be joined are first tacked together by welding at points about 2 inches apart. Large work is held together by clamps instead of by tacking. The clamps must be removed at the right time by a helper. In the case of tacked joints, the tack welding must be remelted by the final welding and so be incorporated in the weld proper.

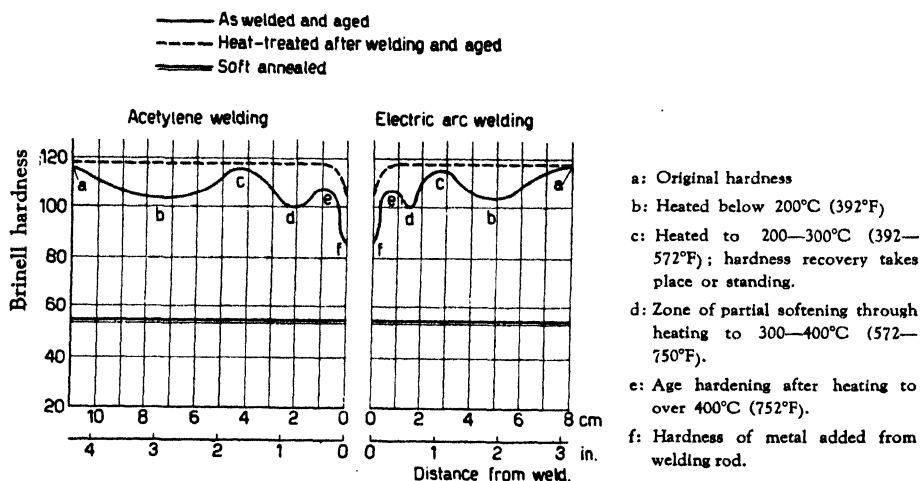


Fig. 347. Curves of hardness for electric arc and acetylene welding transverse to the welded joint, for Avional (Duralumin) sheet.

Table 50 gives some operating data for both acetylene and arc welding.

The heating of the weld causes a zone of softening in heat-treated material, and also in work-hardened material, as has already been mentioned and as shown in the graph in Fig. 347. In heat-treatable alloys, this loss of

strength can be made up by subsequent heat-treatment but in the work-hardened alloys the softening remains. The weld itself always shows a reduced elongation and some degree of brittleness owing to its cast structure. With pure aluminium and non-heat-treatable alloys, some restoration of hardness can be imparted by hammering after welding, but this is not recommended for

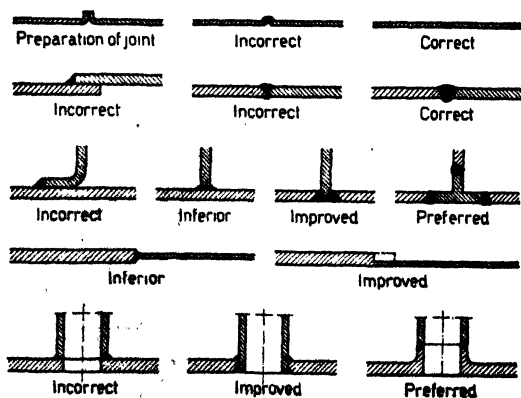


Fig. 348. Methods of jointing by acetylene welding.

heat-treatable alloys owing to the resulting incipient embrittlement of the joint.

The most suitable alloys for acetylene welding are the Al-Mg alloys as these have good strength even in the soft condition. With alloys containing 5% magnesium and over, however, difficulties occur in welding due to the formation of blowholes.

TABLE 50

ANALYSIS OF TIME AND CONSUMPTION OF WELDING MATERIAL  
FOR THREE FEET OF WELDED JOINT

Item	Oxy-acetylene welding					Electric arc welding				
	Thickness of sheet-inches					Thickness of sheet-inches				
	.120	.160	.200	.240	.320	.120	.160	.200	.240	.320
Operation times - seconds										
Tacking (incl. straightening)	35	64	135	240	250	25	25	35	35	40
Warming up	55	82	190	220	230	—	—	—	—	—
Welding	362	525	590	720	748	170	208	220	240	255
Total time	452	671	915	1180	1228	195	233	255	275	295
Materials used and consumed:	Filler rod length used 32 inches					Electrode length: Up to .160"; 15 inches used, 16 inches total Over .160"; 17 inches used, 18 inches total				
Filler or welding rod dia. - ins.	.200	.200	.200	.320	.320	.160	.200	.240	.320	.400
Filler rods used	1	2½	2½	1½	2	—	—	—	—	—
Electric welding rods used.	—	—	—	—	—	3½	2-2/3	3	3½	2½
Weight of filler or welding rod used - lbs.	.09	.20	.25	.42	.47	.09	.13	.21	.42	.44
Weight of flux in powder form (Lumiweld A)-lbs	.026	.033	.037	.04	.05	—	—	—	—	—
Acetylene - cu. ft	.17	1.4	2.5	3.5	9	—	—	—	—	—
Oxygen - cu. ft	.6	1.2	2	3	7	—	—	—	—	—

Fig. 348 shows some examples of the correct arrangement at joints of welded work, and Table 51 gives a selection of physical properties of unwelded and welded materials as well as the effect of a subsequent heat-treatment, for acetylene and electric arc welding.



TABLE 51

MECHANICAL PROPERTIES OF ACETYLENE AND ELECTRICALLY ARC WELDED ALUMINIUM AND ALUMINIUM ALLOY SHEETS

Base Metal	Filler Metal	Welding Process and after-treatment	0.2 % Proof Stress		Tensile Strength		Elongation $l = 11.3/\sqrt{A}$ %	Fatigue Strength (10 <sup>7</sup> reversals)	
			Tons/ sq. in.	1000 lb/sq. in.	Tons/ sq. in.	1000 lb/ sq. in.		Tons/ sq. in.	1000 lb/ sq. in.
99.5 Al	O	—	1.5—2.5	3—5	4.5—6	10—13	30—40	2.5—3	5.5—7
	H	—	7—10	16—22	8—11	18—24	2—8	4—4.5	9—10
	H	—	2—3	4—7	4.5—6	10—13	20—25	2—2.5	4.5—5.5
	H	99.5 Al Acetylene Electric	3—5	7—11	5—6	11—13	5—8	—	—
Peraluman3 (Al-3Mg)	O	—	6—9	13—20	13—16	29—36	18—26	6—7	13—16
	H	—	16—20	36—45	19—22	43—49	4—7	6.5—7.5	14—17
	(Pe 3)	—	6—9	13—20	13—15	29—34	10—15	4.5—6	10—13
	cf BA21, 52S H	Pe 3 12Si } Electric	8—10	18—22	9—11	20—24	1—2	—	—
Peraluman5 (Al-5Mg)	O	—	8—11	18—24	16—20	36—45	18—28	6—7	13—16
	H	—	18—22	40—49	22—25	49—56	6—12	6.5—7.5	13—17
	(Pe 5)	—	8—11	18—24	16—19	36—43	10—15	5—6	11—13
	cf BA28 H	Pe 7 Electric	8—10	18—22	9—11	20—24	1—2	—	—
Anticorodal (Ac)	O	—	2.5—5	5—11	6—9	13—20	20—30	—	—
	T	—	17—24	38—54	20—27	45—60	10—14	5.5—6	11—13
	(Al-Si-Mg)	4 Si Acetylene N	5—10	11—22	9—13	20—29	3—10	4.5—6	10—13
	T	Ac Acetylene N	5—10	11—22	9—13	20—29	3—10	4.5—6	10—13
cf BA24, BA25, 51S	T	Ac Acetylene A	17—19	38—43	20—23	45—52	8—14	4.5—6	10—13
	T	4 Si Electric N	11	24	12	27	1.5	3.5—4	8—9
	T	12 Si Electric N	12	27	13	29	2	—	—
	T	Ac Electric N	9	20	9	20	1.5	—	—
Avional M (Duralumin) (Al-Cu-Mg) (Av-M)	O	—	5—8	11—18	12—16	27—36	16—22	—	—
	T	—	18—22	40—49	27—32	60—72	16—20	7—8	16—18
	T	Av Acetylene N	11—14	24—31	17—20	38—45	2—8	—	—
	T	Av Acetylene A	14—18	31—40	24—28	54—63	7—15	5.5—7	12—16
BA350, 17S	T	Av Electric N	15	34	17	38	1	4.5—5	10—11
	T	12 Si Electric N	16	36	20	45	1.5	—	—
	T	Av Electric A	17	38	21	47	2.5	—	—
	T	4 Si Electric A	16	36	21	47	2.5	—	—

See Tables 3 &amp; 4 for Alloys.

O — Soft

H — Hard rolled

T — Fully heat-treated

A — Heat-treated after welding

N — As welded — no after-treatment

This table also gives the figures for electric arc welds, enabling a comparison of acetylene and electric welding to be made. Fig. 349 shows some storage tanks of 70,000 to 110,000 gallons capacity, of pure aluminium welded sheet construction, while Fig. 350 shows work in progress on welding large tanks for the chemical and food manufacturing industries.



Fig. 349. Welded pure aluminium storage tanks of 70,000 to 110,000 gallons capacity (Schweisswerk Schlieven).

In welding castings as is often done for repair jobs, the part must be carefully cleaned and the edges of the joint must be bevelled. Owing to the greater rigidity and smaller elongation of castings than wrought parts,



Fig. 350. Welding in process (Schweisswerk Schlieven).

the danger of cracking at the weld is greater in the former. To minimise this, the entire casting is slowly heated to  $400^{\circ}\text{C}$  ( $752^{\circ}\text{F}$ ) and is maintained at this temperature during welding. It is important in welding that the metal surrounding the weld is heated uniformly. Fig. 351 shows how, in

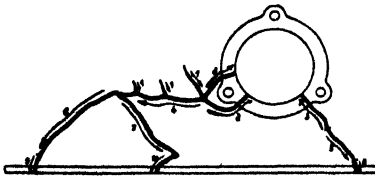


Fig. 351. Method of carrying out a welding repair job.

welding a broken casting, the welding is constantly being changed from one place to another in accordance with the numbered sequence shown. Furthermore, welding must take place from the centre towards the periphery, so that the terminations of the welds at the edge of the casting are made last.

## 7. ALUMINO-THERMIC WELDING\*

Alumino-thermic welding is used for the joining of lengths of cable in position. In this method, the burning of a sintering thermic mixture which is packed in a sheet steel mould heats the ends of the cable in the mould to melting point. Fig. 352 shows how the cable is secured in a screw operated clamp for the operation. As soon as the joint begins to melt, the two ends of the cable are advanced about 1 inch towards each other, thus forcing oxide skin with some molten aluminium out of the joint. After removing the remaining sintered mixture and the two-part sheet steel mould, the joint is cleaned up and will be found to be soundly welded as in Fig. 353. An

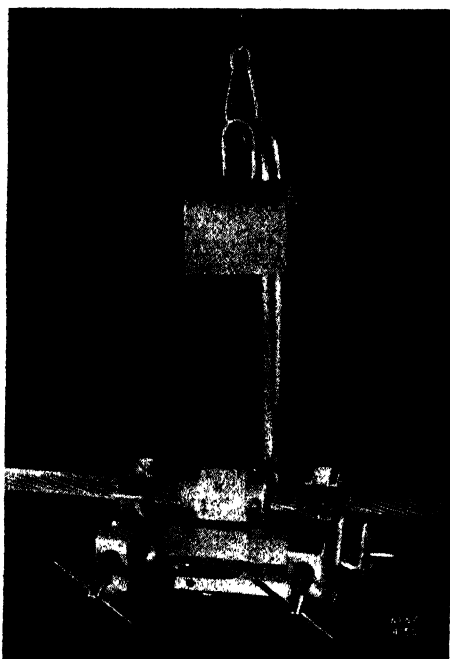


Fig. 352. Tension clamp for alumino-thermic cable welding, "Alutherm".



Fig. 353. Alumino-thermic welds, "Alutherm".

Top and bottom = cable to cable      Middle = cable to solid bar

advantage of this process is that a skilled welder is not required, but by following the prescribed method, any linesman can make such welds. A welded joint retains its high conductivity indefinitely, whereas mechanical joints in cables may suffer some deterioration in this respect in course of time if oxidation penetrates.

\* Trade names Alutherm and Thermit.

## 8. ELECTRIC ARC WELDING

The advantages of electric arc welding over autogenous oxy-acetylene welding are a lower operating cost, a greater speed of working and a more localised heating of the part, which results in lower thermal stresses. A disadvantage is the lower elongation across the weld, due to the more localised heating.

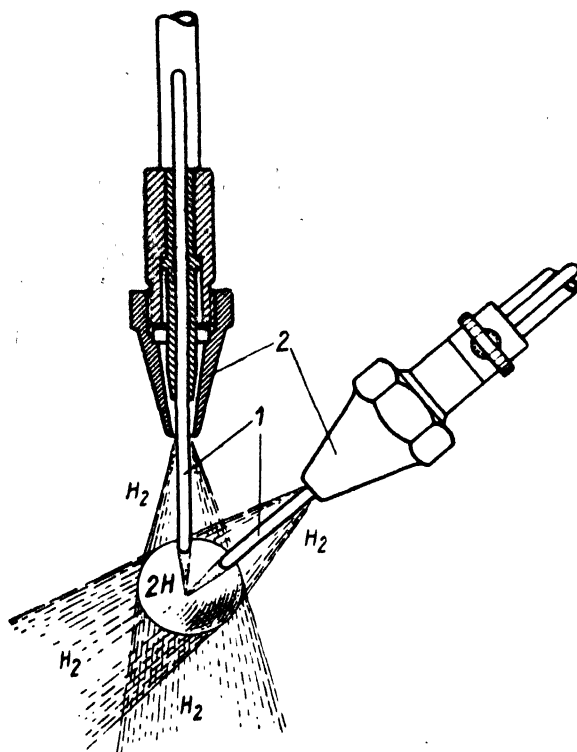


Fig. 354. "Arcatom" welding torch.

a. Atomic arc welding

Langmuir of the General Electric Co. (U.S.A.) is responsible for having introduced a combination of arc and hydrogen welding which has been designated "Arcatom" \* welding. As shown in Fig. 354, the arc burns between two tungsten electrodes 1, and hydrogen gas is effused around the electrodes from the concentric nozzles 2, this gas at the temperature of  $2300^{\circ}\text{C}$  ( $4172^{\circ}\text{F}$ ) being in part dissociated from the molecular into the atomic state. At the outer zone of the disc-like arc flame, the hydrogen atoms recombine into the molecular state with evolution of heat. Langmuir estimates the temperature of the outer reaction zone to be  $4000^{\circ}\text{C}$  ( $7232^{\circ}\text{F}$ )

\* Registered trade mark.



Fig. 355. Equipment for "Arcatom" welding (LANGMUIR).

In this condition, the heat energy of the arc is transferred to the weld in a concentrated manner. The hydrogen atmosphere enveloping the arc protects the weld against oxidation. Nevertheless, welding is carried out with a flux, as in the case of acetylene welding, and this is painted thinly on the sheet edges beforehand. The striking voltage of the arc amounts to 300 volts in the hydrogen atmosphere, while the working voltage is 60 to 100 according to the electrode distance. The welding current varies between 20 and 70 amps. Fig. 355 shows the equipment used for atomic arc welding.

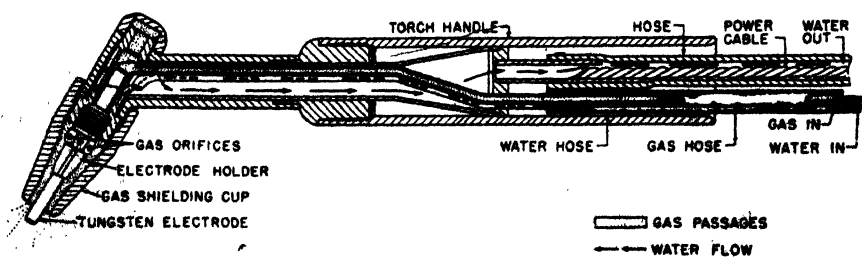


Fig. 355a. Argon-shielded arc welding electrode.



Fig. 355b. Welding with argon-shielded arc. (Linde Air Products Company.)

#### b. Argon arc welding

Further developments of the gas-shielded arc welding are the Heliarc and Argonarc methods. As the names connote, the first method uses helium, and the latter argon as the protective gases. Whereas in atomic arc welding the arc burns between two tungsten electrodes and serves principally for the atomic dissociation of the hydrogen, in shielded arc welding, the arc burns between a tungsten electrode and the work, and is enveloped in the protective gas, which prevents the oxidation of the light metal. Fig. 355a shows an argon-shielded arc welding electrode, and Fig. 355b the method of using it. Owing to the high density of argon, the consumption of this gas is much less than of helium and amounts to .2—.3 cubic feet per minute. The rate of welding is largely dependent on the operator and in general is less than that of ordinary arc welding. The process has the big advantage that it can be carried out without fluxes, as the thin natural protective oxide film on the aluminium does not prevent a sound weld, and the protective gas prevents any oxidation of the molten aluminium. As the striking of the arc by rubbing the tungsten welding electrode on the work would give rise to alloying between the tungsten and the aluminium, this method of striking is not

permissible. For this purpose a high-frequency alternating voltage is superimposed, which causes the arc to start when the electrode distance has been reduced to a small value, e.g.,  $1/8$  inch. The process is very suitable for automatic welding, as the rate of consumption of the electrode is very small indeed, and replacement is only necessary at very long intervals. Shielded arc welding is suitable for sheet thicknesses of .040 to  $1/8$  inch.

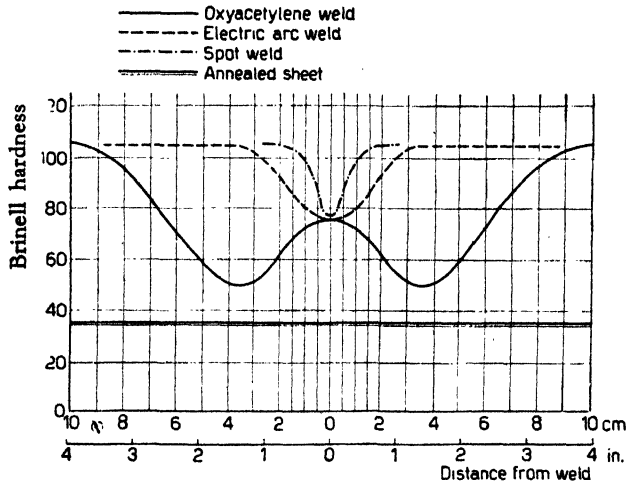


Fig. 356. Variation of hardness across a weld in Anticorodal (Al-Si-Mg alloy).

### c. Arc welding

The arc welding of iron was introduced by SLAVIANOFF in 1892. This process was first used for aluminium in 1928, with coated electrodes, to give a stable arc and to cause solution of the aluminium oxide. The coating has to stand more exacting conditions than in acetylene welding; in particular it must stand up to the higher temperatures of the arc without

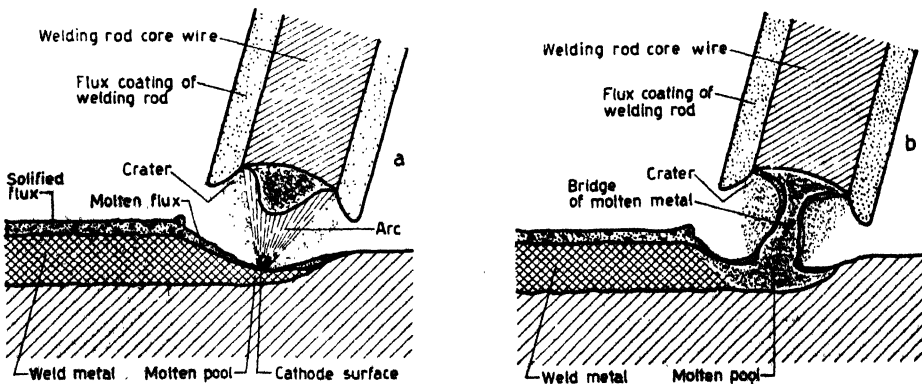


Fig. 357. Formation of metal drops in electric arc welding (Schaerer).

vapourising excessively. Otherwise it has to fulfil the conditions of an acetylene welding flux.

The intense local heat of the electric arc brings a greater risk of melting through the work than with acetylene welding, and therefore sheets thinner than .080 inch are not arc welded. This risk of melting through is minimised by the use of a backing plate, which can advantageously be made with a groove of depth equal to  $1/3$  that of the sheet. The rapid rate of welding reduces the extent of the zone of softening as compared with acetylene welding. Fig. 356 shows the extent of the zone of the softening in Anticorodal (Al-Si-Mg) not heat-treated after welding, following autogenous, arc and spot welding. The distance of the electrode welding rod from the work in arc welding is  $\frac{1}{4}$  to  $\frac{3}{8}$  inch, which permits the droplets of molten metal from the welding rod to bridge the gap as shown in Fig. 357. Adequate visual protection must be afforded to the operator against the intense brilliance of the arc. The welder generally prefers a visor screen in his left hand to a helmet, thus keeping his left hand occupied. The best glass for the screen is a combination of dark green and cobalt blue, the cobalt glass cutting off the yellow sodium light.

It is important that the flux should be easily detachable from the welded joint when cold. The last traces are removed with the help of a pointed hammer and a wire brush. A final washing is subsequently given as for acetylene welds. In changing electrodes, about  $\frac{1}{2}$  inch of the completed weld has to be fused again, but in spite of this it is usually possible to discern the starting points of new electrodes. The most skillful operators, however, arrange that a second welder with a new rod connected in a parallel circuit with that in use takes the arc from the old rod while it is still in use and continues the welding without any interruption. The first welder then has an opportunity, while the relief electrode is welding, to

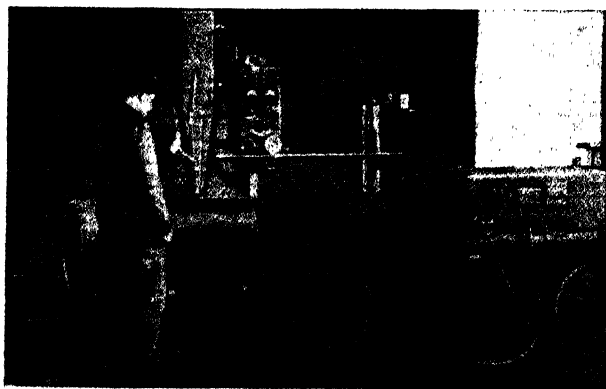


Fig. 358. Automatic electric arc welding set (KJELLBERG).

fit a new rod in his electrode holder and to be ready to resume his turn of welding on the expiry of the second electrode, and so on. The same sequence of operation is carried on in the KJELLBERG automatic arc welding set as shown in Fig. 358. This produces a welded joint of any desired length without





Fig. 359. Arc welding all-light-metal coaches for the Chemins de Fer du Nord.

interruption, the operator simply watching the course of the welding, replacing used electrodes with new rods as often as necessary, and making any adjustments to the apparatus that may be required. Fig. 359 shows one of the earlier large-scale electric arc welding jobs on light metal railway coaching stock for the Nord Railway of France, using an Al-5Mg alloy.

Owing to the presence of the oxide film, the electric arc welding of aluminium requires a striking voltage as high as 60 to 70, while the voltage required for actually welding is 20 to 25. Special welding sets of low reactance are therefore necessary, which give a steep rise of voltage at the moment of striking the arc. If a transformer of the impedance characteristic suitable for steel welding is used, the slow rise of voltage will make it difficult to strike the arc.

Table 52 gives a comparison of the time of burning of electrode, electrode diameter and welding current for the electric welding of sheets of different thicknesses, while further data on arc welding and the properties of welds were given earlier in Tables 50 and 51. For  $\frac{1}{4}$  inch sheet, the edges of the sheet are not bevelled, but above this they are bevelled at  $35^\circ$  for half the thickness, while as shown in Fig. 360, the gap between the plates is  $\frac{1}{3}$  of the thickness. For the thicker plates, it is best to warm the work to  $150\text{--}200^\circ\text{C}$  ( $302\text{--}392^\circ\text{F}$ ). This lightens the work of welding and retards

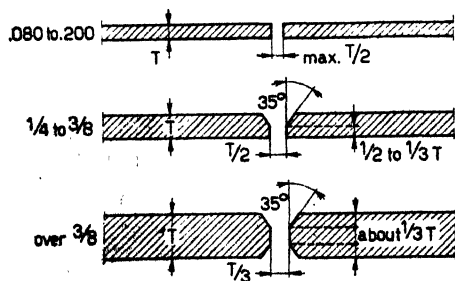


Fig. 360.

Preparation of edges of joint for electric welding.

the solidification of the weld metal, so that more time is allowed for it to become quiescent. With high magnesium alloys, a percentage of the magnesium is lost by volatilisation. Fig. 361a shows a welded joint in an Al alloy with 7% Mg with no preheating, in which blow-holes can be seen at the junction of the weld

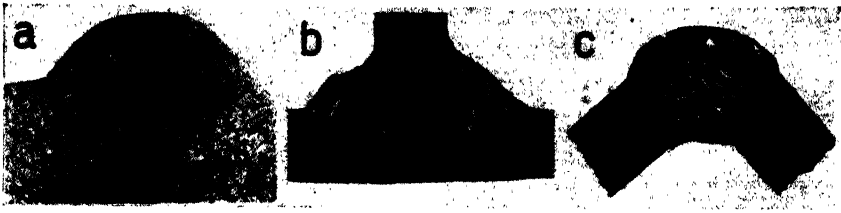


Fig. 361. a) Porous arc-welded joint (not preheated)  
 b) T-joint on pure aluminium plate.  
 c) Angle joint on 5/16 inch pure aluminium plate.

metal and the sheet. If this is preheated, such blowholes will not be present. Fig. 361b and c show welds in 3/8 inch pure aluminium plate, made without a backing plate but with moderate preheating. In the angle joint, the complete penetration of the weld can be seen, also the resulting soundness of the joint.

TABLE 52

ELECTRODE DIAMETER, WELDING CURRENT AND TIME OF BURNING FOR  
 THE ARC WELDING OF PURE ALUMINIUM

Diameter of welding rod, inches	Welding current, amps. Average		Current density amps/sq. inch	Average time of burning of electrode, secs	Calculated melting rate, lb/amp. hr. Average
.100	40—70	(55)	5000—9000	23—29	0.022
1/8	70—100	(85)	5000—8000	31—35	0.023
.160	100—130	(115)	5000—6500	34—37	0.025
.200	130—150	(140)	4000—5000	45—50	0.026
1/4	150—190	(170)	3500—4500	50—56	0.028
5/16	190—240	(215)	2500—3000	65—75	0.029
3/8	240—280	(260)	2000—2500	85—95	0.030

Length of welding rod up to .160 inch, 16 inches  
 " " " " above .160 inch, 18 inches  
 Useable length up to .160 inch, 15 inches  
 " " above .160 inch, 17 inches

## 9. RESISTANCE WELDING

### a. Seam welding Weibel method

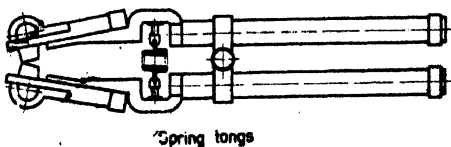
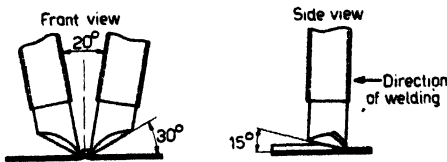


Fig. 362. Weibel electrode tongs for seam welding (K.G. Gabler & Co., Bad Aussee, Austria).

Thin sheets are sometimes welded by the Weibel seam-welding method. In this the edges of the sheets are flanged about 3/32 inch as shown in Fig. 362, and pressed into contact with each other with graphite electrodes in holding tongs. The current passes from one electrode to the other

through the joint and generates heat, bringing the edges of the sheet to the melting point. The electrode tongs are moved along at a slow rate so as keep pace with the melting of the metal. This process can be arranged for mechanical operation, the welding tongs being moved automatically at the desired speed.

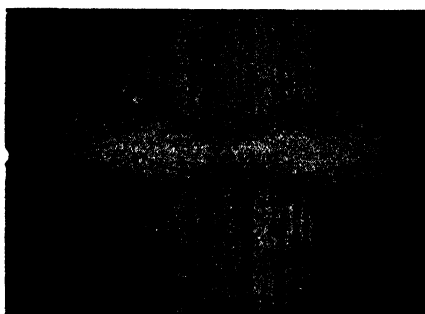


Fig. 363. Longitudinal section through a butt weld showing the flash.

### b. Butt welding

Another form of resistance welding is butt welding, and this is much used for the end-to-end joining of rods and sections. In this process, the sections are clamped in suitably shaped clamps of copper or bronze and are pressed together with spring pressure which is capable of being accurately discontinued. The contact resistance between the rods or sections

causes a generation of heat under the passage of the electric current which raises the metal to the melting point at the joint, on which the sections are pressed together and the oxide skin with some metal is pressed out of the joint as a flash as in Fig. 363. As soon as the movement together commences, the current is automatically cut off. Sometimes, after cleaning up the weld, the joint is annealed with a smaller current to relieve stresses. For successful butt welding, the current strength and pressure must be accurately regulated to the best values. These conditions have to be found by trial for each alloy and each section. Beside pure aluminium, the medium strength Al-Mg (Peraluman type, BA21, 52S) alloys are those most suitable for butt welding. Owing to the rapid solidification, the zone of melting is extremely fine grained. Butt welding is much used for joining wires in electric cables, and in these the mechanical properties of the welds

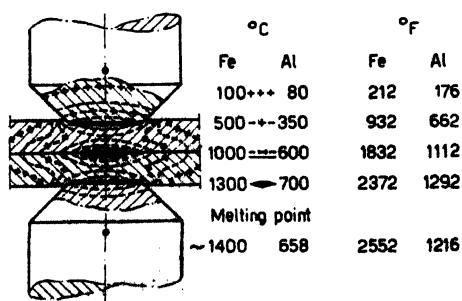


Fig. 364. Isothermal zones in spot welding, showing temperature distribution.

permit a further drawing of the wire to a thinner gauge. The quality of the weld is best tested by a wrapping test round the wire itself.

### c. Spot welding

Another method of resistance welding is spot welding. In this, as shown in Fig. 364, the current passes (as in butt welding) from the impressed electrodes through the

sheets to be joined. Thus the electrodes must make the best possible contact with the work so that the minimum possible heat is generated at the electrode contact surfaces, and the contacting surfaces of the metal to be joined, with their greater contact resistance, may be heated to melting point. Table 53 shows how the physical properties of aluminium differ considerably from steel. The low electrical resistance and high heat conductivity of aluminium imply that for spot welding practically double the welding current is needed for aluminium as for steel, and, owing to the unfavourable proportion of the contact resistance to the overall resistance across the spot welding machine, 4 to 5 times the primary current is necessary for aluminium as for steel. Thus a steel sheet .040 inch thick requires 10,000 amps, while an aluminium sheet of similar thickness requires 18,000 amps to give a sound spot weld.

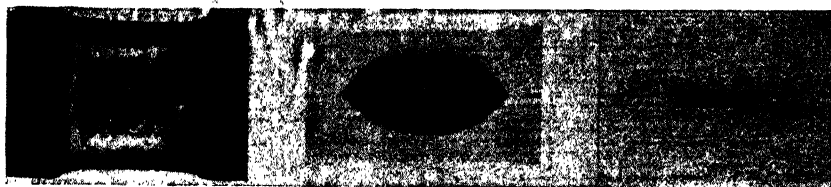


Fig. 365. Effect of current strength on the size of weld lens or nugget in spot welds.  
Left: Current strength too high Middle: Correct current strength Right: Current strength too low

To ensure the lowest possible contact resistance between the electrodes and the aluminium, the oxide skin should be removed from above and below the weld by brushing or dipping, while it is better to leave it undisturbed between the sheets. It has even been proposed to thicken up the oxide skin at the welding spot between the sheets to a uniform thickness of 0.00002 inch or thereabouts by chemical or anodic oxidation.

The thickness of the oxide skin on light metals varies between 0.000002 and 0.00001 inch (0.05—0.2  $\mu$ ) according to the method of manufacture. The correct degree of current strength must therefore be found by trial and error for the various materials so that a correct weld "lens" or "nugget" of about half the thickness of the sheet is formed, as is shown in the section of a weld in Fig. 365, centre. With too high a current strength or too great a duration, the lens extends across the full thickness of the sheet as far as the outer surface, Fig. 365, left, and is then frequently porous and penetrated by cracks. Due to the softening of the material, the electrodes sink in too far under their pressure so that burning of the electrode tips may take place. With too low a current strength, only an incomplete weld of low strength is formed (Fig. 365, right).



JUNKERS has proposed an arrangement comprising a brass band .020 inch thick which is moved between the electrode and the work. After every weld, this band is moved forward by the diameter of a weld so that a new portion of the strip is available for contact. The brass strip is in the form of an endless band and, before the used surface comes again to the working point, it is freed mechanically from all fouling. With this arrangement, large numbers of spot welds can be made without interruption.

TABLE 54

## SPOT WELDING CONDITIONS

Material	Thickness inch.	Current, amps.	Welding time half cycles.	Electrode pressure, lbs.	Electrode diameter ins.	Strength of spot weld* lbs.
Aluminium	.040	20,000	16	200— 600	0.39	200
	.080	28,000	24	600— 800	0.46	300
	.120	35,000	30	800—1200	0.46	400
Peraluman 5 (Al-5Mg.)	.040	20,000	12	450— 650	0.39	450
	.080	26,000	20	750—1000	0.46	1200
	.120	32,000	26	1100—1300	0.46	1700
Anticorodal (Al-Si-Mg) (Cf. BA25, 51S, etc.)	.040	20,000	12	450— 650	0.39	400
	.080	26,000	20	750—1000	0.46	750
	.120	32,000	26	1100—1300	0.46	1000

\* To  $\pm 25\%$



Fig. 367. Test of spot welds to destruction.

Testing of the welds is done mechanically by fracturing, the weld spot being torn out of the material as shown in Fig. 367. Fig. 368 shows the effect of alloy and thickness on the shear strength of sound welds. It can be seen that soft pure aluminium has the lowest strength.

For large size jobs, a correspondingly great reach of the arms of the machine is required. This increases the electrical losses, so that, for larger machines, for equal sheet thickness, a considerably greater electrical rating of the machine is required. An increase in arm length from 8 to 40 inches

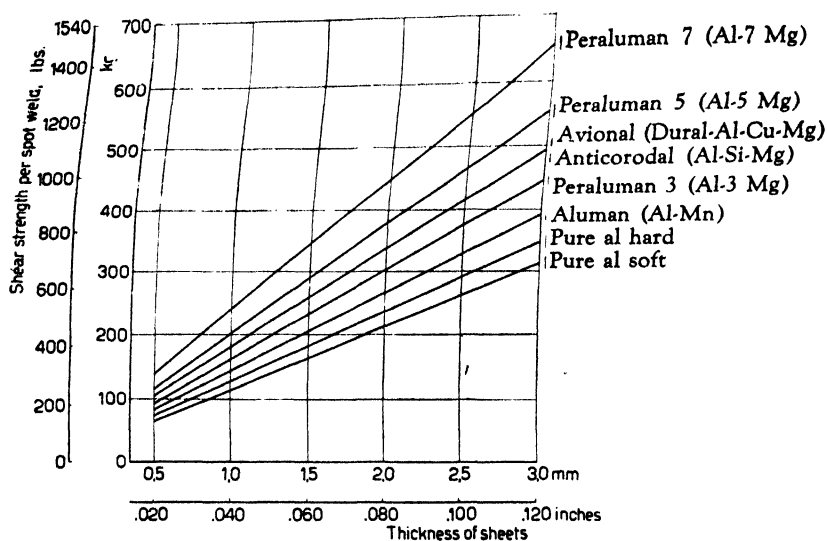


Fig. 368. Shear strength of spot welds in different alloys.

reduces the effective rating at the welding tips by half. To overcome this difficulty, Berghaus has developed the 2-point welding machine as shown diagrammatically in Fig. 369, on which two spot welds are made simultaneously with medium frequency current, the welding current unaffected by the jaw length, as will be seen from the illustrations, always taking the shortest path to a welding spot. The pitch of the spot welds is also a factor affecting the welding. With a small interval between welds, below  $1\frac{1}{2}$  to  $2\frac{1}{2}$  inches and with thin sheets .040 inch to  $\frac{1}{8}$  inch thick, the proximity of the adjacent spot weld reduces the size of the weld lens, so that a correspondingly heavier current must be employed for equal welds.

There are two classes of spot welding machines: the older transformer type machines as used for the spot welding of steel; and the stored-energy, heavy-discharge, "shot welding" machines as recently developed specially for light metal welding.

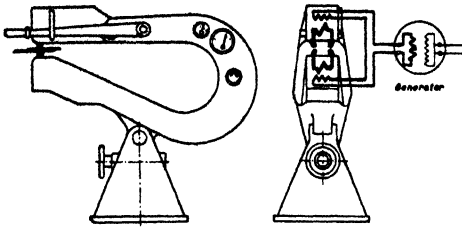


Fig. 369. Welding frame and wiring diagram of the Berghaus 2-point spot welding machine.

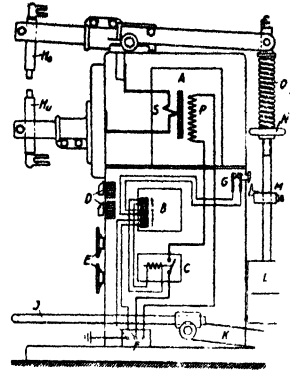


Fig. 370. Wiring diagram of the transformer-type spot welding machine (Schlatter, Zollikon).

The wiring diagram of a transformer machine is shown in Fig. 370. These machines are single phase, and for the higher power units it may be necessary to have a phase changer or motor-generator to avoid destructive surges in the mains. The control gear is always on the high tension side, electronic control being preferred as mechanical control cannot give the required degree of range and accuracy. Tap-changing transformers, giving a range of secondary voltage of 5 to 10 volts with about 20 steps, are used, while



Fig. 371.

650 KVA spot welding machine for railway coach construction (Brown, Boveri & Co.).



the grid control is variable to give a welding time of 10 to 50 half cycles. In small machines the electrode pressure is obtained by means of a foot pedal working through interchangeable springs, while large machines and those with automatic control of the welding cycle have mechanical pressure arrangements, operated by compressed air or hydraulically. The secondary current must be adequate for the largest welds that may have to be made, and for sheets .040 inch thick must be 20,000 amps, 1/8 inch 40,000, and 1/5 inch 60,000 amps. The corresponding ratings of such machines are 150, 300 and 500 KW respectively. The electrodes are generally made of copper and are watercooled, and it is an advantage to use a cooling liquid at  $-10^{\circ}\text{C}$  ( $14^{\circ}\text{F}$ ) to avoid the fouling of the electrodes. A big spot welding machine of 650 KVA input with arms 5 feet long for the spot welding of railway coach bodies is shown in Fig. 371.

With conversion of the AC to single phase, the control of the welding machine is frequently arranged in the motor-generator, the excitation of the welding generator being used for this. In such a case, the current strength can be modulated during the welding cycle. Careful tests, however, have failed to demonstrate any great advantage for current modulation.

The disadvantage of transformer machines is that the energy available at the welding point and therefore the size of the fused lens or nugget is greatly dependent on the contact resistance between the electrode tips and the work, as well as between the parts to be joined. This effect is less in the heavy-discharge type of machine.

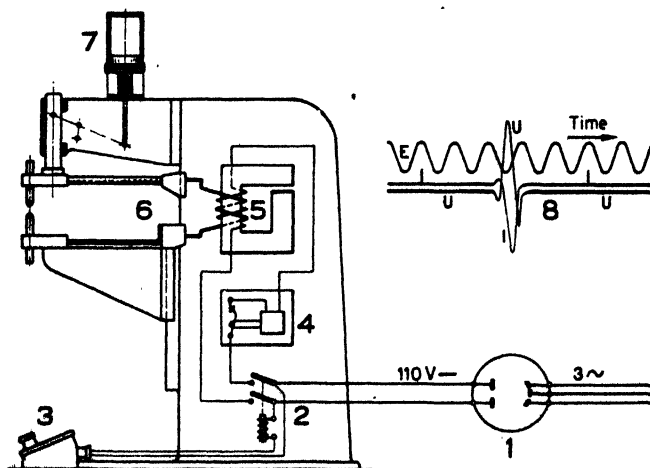


Fig. 372. Sciaky heavy-discharge spot welding machine.

- 1 Mercury arc rectifier
- 2 Main switch
- 3 Foot-operated barrel switch
- 4 Relay for input control and breaker
- 5 Air-gap transformer
- 6 Secondary (welding) circuit

- 7 Pressure cylinder
- 8 Oscillograph diagram
- E Supply voltage
- U Welding voltage across electrodes
- I Welding current in electrodes
- Upper right = Oscillogram of welding current

A leading example of the heavy-discharge principle is the SCIAKY machine, for which a wiring diagram is shown in Fig. 372. In this the 3-phase alternating current is converted to single-phase pulsating current in a mercury rectifier and this is led to the primary coil of a specially designed transformer. On sudden interruption of the current, the flux change from the primary coil gives rise to a high self-induced EMF, which causes a very high current surge in the secondary, as shown on the oscillograph diagram in the illustration, of only a few fiftieths of a second duration. As this surge has a higher voltage than the welding current from a transformer machine, the welding energy is less dependent on the contact resistances of the tips. Control of the machine is effected by the magnetisation of the transformer by the direct current. A further advantage of this stored-energy machine is the smaller current surge in the supply mains.

Another variety of heavy-discharge type of welding machine is the condenser machine, in which the continuous current charges a condenser of 4 000 to 28 000 mfd. After it is charged, the condenser is discharged across the welding transformer and creates a momentary welding current surge in a similar manner to the SCIAKY machine. The diagram of the machine is shown in Fig. 373.

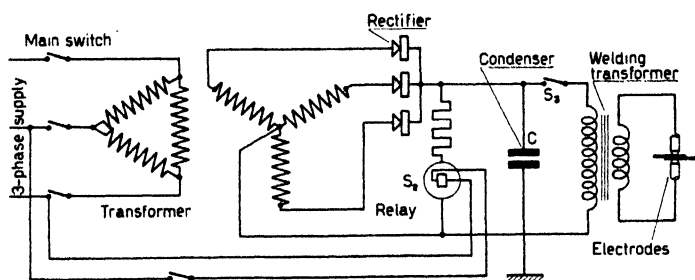


Fig. 373. Wiring diagram of a capacity spot welding machine.

## CHAPTER XVI : RIVETING

### 1. GENERAL

In the case of heat-treated or work-hardened alloys, there is a loss of strength on heating when welding or soldering. When this loss is not permissible, the joint should be made by riveting or spot welding. In riveting, the selection of the correct material for the rivet is important. The rivets should not only possess the highest possible strength, but should also have an electrochemical potential similar to that of the material to be joined. This is generally the case when both parts to be joined are of the same material. When, however, clad Al-Cu-Mg alloy (Duralumin type), plated with pure aluminium, is riveted, the selection of the rivet material needs special consideration. Rivets of Al-Si-Mg alloy are best in this case. If rivets of Al-Cu-Mg alloy should be used, some provision for corrosion protection for the rivet must then be made. Al-Si-Mg and Al-Mg alloys have the same solution potential as the pure aluminium cladding layer, but these have a somewhat lower strength than the Al-Cu-Mg alloy part. Fig. 374 shows the slight corrosion that has taken place where there is a difference of composition between sheet and rivet, the Avional or Duralumin (Al-Cu-Mg) rivets age-hardened at room temperature having an electrochemical

solution potential of  $-0.6$  volt, and warm-aged Avional (Duralumin) sheet one of  $-0.7$  volt; the latter becomes the negative pole and tends to be electrochemically attacked around the rivet head.

The naturally ageing rivet alloys can only be headed for a limited time after heat-treating and quenching. As shown in Fig. 32, the rate of age hardening increases at higher temperatures. Hence by keeping in a refrigerator, rivets may be retained in a workable condition for 24 hours or more.

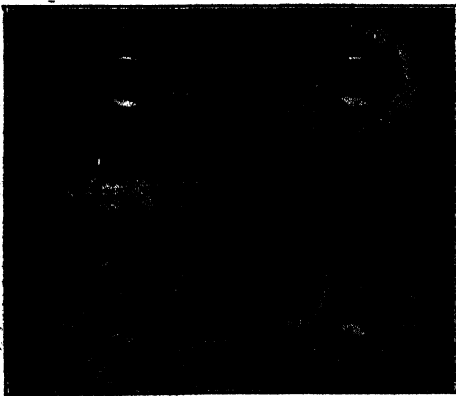


Fig. 374. Corrosion around rivets due to difference in material of rivet and sheet.

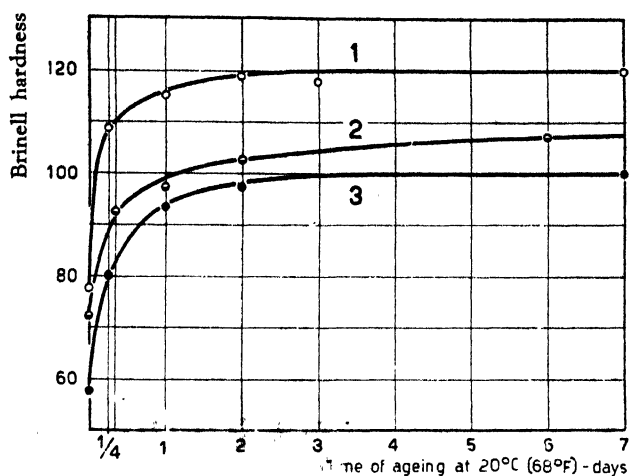


Fig. 375. Hardening curves of different Avional rivet alloys (Al-Cu-Mg — Duralumin type).

Composition of alloys — %					
No.	Cu	Mg	Mn	Si	Fe
1	4	0.8	0.7	0.6	0.2
2	4	0.8	0.5	0.2	0.2
3	4	0.8	—	0.2	0.2

Mechanical properties of the above alloys

No.	Proof stress		Tensile strength		Elongation	Brinell hardness	Shear strength	
	Tons /sq. in.	1000 lb /sq. in.	Tons /sq. in.	1000 lb /sq. in.			Tons /sq. in.	1000 lb /sq. in.
1	18	40	29	65	19	120	—	—
2	15	34	28	63	20	105	17	38
3	14	31	25	56	23	100	16	36

At 20°C (68°F) the standard Avional (Duralumin) alloy cannot be headed after 6 or 8 hours without cracks appearing in the head. The aim has therefore been to develop alloys that age-harden less rapidly. Fig. 375 shows the curves of age-hardening of some different rivet alloys, and the annexed tables show the compositions and mechanical properties of most importance in rivet alloys of this type. The artificial- or warm- ageing alloys such as Anticorodal (Al-Si-Mg), afford an unlimited period before hardening, if they are quenched from a lower temperature (480°C, 896°F) than the normal quenching temperature (530°C, 986°F). This does not affect their corrosion resistance, unlike the Al-Cu-Mg alloys. For the heat-treatment of rivets, small firms which only use a small number of rivets in a day may make use of small salt baths as in Fig. 376.

An accurate temperature control is essential as the solution heat-treating temperature must be held between 500° and 510°C (932° to 950°F) if maximum corrosion resistance is to be assured.

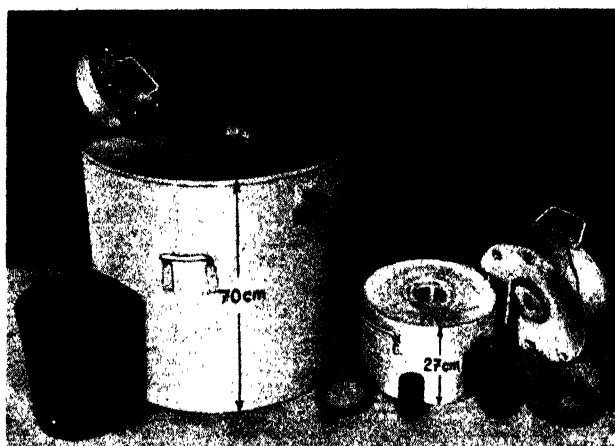


Fig. 376. Small salt bath for the heat-treatment of rivets.

If the rivets are to be heat-treated after the heading operation in which the machine-made first head is formed, they should not be made from soft annealed wire, as an undesirable coarse grain-size may arise in the regions of least deformation. A rivet wire of intermediate temper with 25% cold work is therefore used. In the driving of the rivet shank through the rivet hole and the forming of the closing head, there is a further increase of strength, the tensile and shear strengths being increased by about 1.5 tons/sq. in. (3000 lb/sq. in.). If it is desired to obtain the greatest possible weight saving, the closing head can be made a little smaller than the machine made head. Table 55 shows the distinguishing marks of various rivet alloys as used in Britain and Switzerland.

TABLE 55  
DISTINGUISHING MARKS OF RIVETS

Alloy Type	British practice			Swiss VSM 131 30 2nd revised draft colour
	Rivet alloy	Spec. DTD 913, colour	Aircraft marks *	
Al-Cu-Mg	2L37	Not coloured	D	Grained surface to rivet head do
Al-Cu-Mg	DTD 327	Violet	S	
Al-Mg5	DTD 303	Green	X	1 groove in the snap
Al-Mg7	DTD 404	Red	—	—
Pure Al	L 36	Black	—	—
Al-Mn	—	—	—	2 grooves in the snap

\* In Great Britain after closing, the heads are embossed with these marks, either in relief or impressed.

## 2. CALCULATIONS FOR RIVETED JOINTS

The basis of all calculations of riveted joints is a knowledge of the mechanical properties of the material to be joined, and of the rivets. Beside the more usual information, the shear strength and fatigue strength of the rivets and the bearing strength of the members are the factors of importance. In contrast to steel riveting, it is to be noted that light metal rivets are always driven cold and therefore do not contract as the steel does on cooling, whereby the steel rivet head is pressed tightly on the plates and clamps them firmly together. The light metal riveted joint thus does not allow of transfer of load from one member to another by friction, but shear and bearing stresses alone take care of this. In a member loaded in tension, considerable concentrations of stress occur at the edges of the holes, which may amount to several times the magnitude of the mean stress in the member. Thus the members are stressed more highly than the rivets with their more advantageous circular sections. Fig. 377 shows the distribution of stress in the members on planes between rivets in the upper illustration, and on planes through the rivets in the lower. In the upper illustration, it can be seen that there is a maximum of stress on the centre line beyond the first rivet, while behind the first rivet, on the other hand, the stress on the centre line is lower due to the rivet hole. In the lower illustration, the peaks of stress at the edges of the rivet holes can be clearly seen. The diminishing loads on the successive rivets can also be seen, the first rivet carrying about  $1/3$  of the total load of the five. Table 56 shows

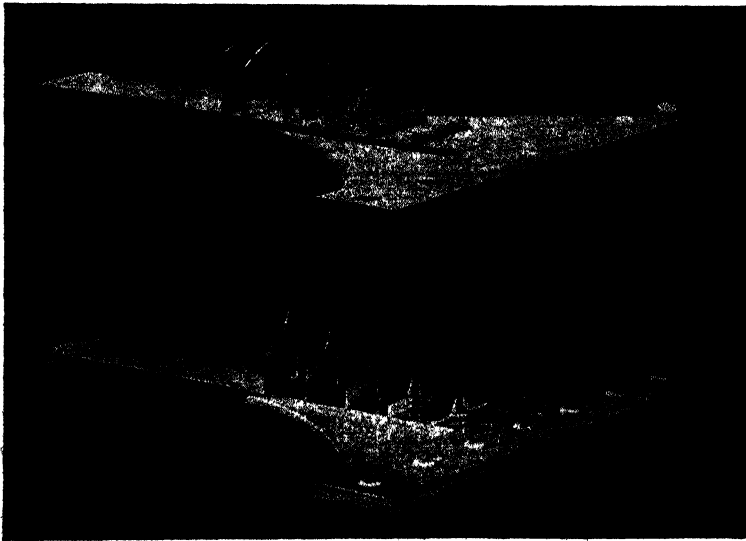


Fig. 377. Stress distribution in a riveted joint. (von Burg, AIAG, Neuhausen, Switzerland)

the distribution of load on 3 and 5 rivets in line, and the maximum stress in the plate at each rivet hole.

TABLE 56

DISTRIBUTION OF LOAD ON RIVETS AND MAXIMUM PLATE STRESS  
AT RIVET HOLES IN A RIVETED JOINT

Rivet number	Line of 3 rivets				Line of 5 rivets			
	Load on rivet		Max. plate stress at rivet hole		Load on rivet		Max. plate stress at rivet hole	
	Tons	Lbs	Tons /sq. in.	1000 lb /sq. in.	Tons	Lbs	Tons /sq. in.	1000 lb /sq. in.
1	1.07	2400	10.8	24	0.65	1460	6.3	14
2	0.52	1200	3.8	7	0.40	900	4.1	9
3	0.32	700	1.5	3.3	0.33	740	3.1	6.7
4					0.29	650	2.2	5
5					0.25	550	0.7	1.6
	1.92	4300			1.92	4300		

It can be seen from this that the maximum stresses are lower with five rivets taking the load than with three. Fatigue tests on riveted joints show that frictional oxidation under the rivet head weakens the material and may lead to failure not directly through the rivet hole (Fig. 378). To avoid this, one method is to use a substantial cover strip or washer strip between the rivet heads and the members of the joint, and to paint all contacting surfaces before assembly with a tough paint which will not become brittle with lapse of time (Fig. 379). The first rivet in the joint may be reinforced in shear by means of a steel sleeve around the shank.

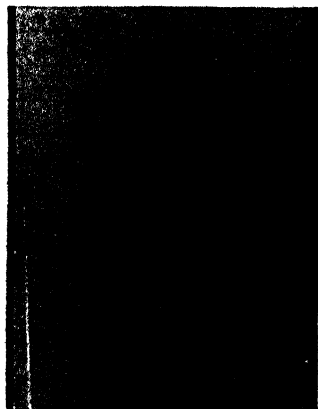


Fig. 378. Fracture of riveted joint under fatigue loading due to frictional oxidation.

The proportion of rivet diameter to residual width of plate at the side of the rivet hole should be such that the shear stress in the rivet is equivalent to the tensile stress in the plate, using the same factor of safety in the rivet and in the plate. Owing to the concentrations of stress at the edges of the holes, these proportions cannot be simply expressed, and extensive static and dynamic tests of different rivet arrangements are necessary to provide information on the best proportions. The best ratio between rivet diameter and grip length is found to be 1.25 in static loading and 0.7 in dynamic, which means that under pure dynamic conditions the rivet should be

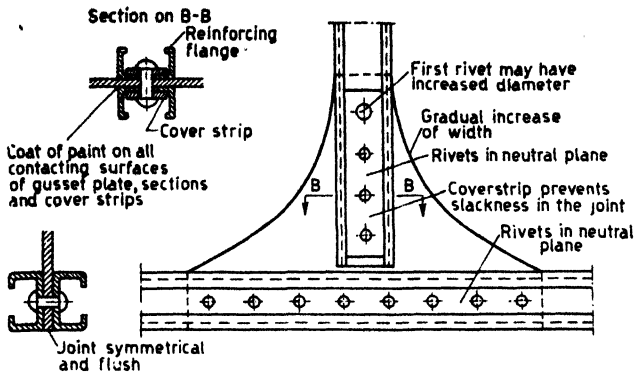


Fig. 379. Detail of rivet joint.

only about half the diameter of that used for static loads. Since, however, it is mostly combined static and dynamic loads that have to be contended with, an intermediate value is usually selected, the diameter generally being about equal to the grip length.

### 3. SHAPES OF RIVET

A number of different shapes of rivet, as shown in Fig. 380, are used in light metal riveting practice. Beside the common shapes of steel rivets, special shapes have been brought into use, such as the pan head, conical head and various countersunk heads all of which require less work to form the head. If the edges of the sheet are dimpled in, the transfer of stress is distributed over a greater area and the shear stress in the rivet shank is reduced. With this method, flush riveting, so much desired in aircraft on account of the reduced aerodynamic drag, becomes quite practicable. Table 57 gives the work required for forming different shapes of rivet

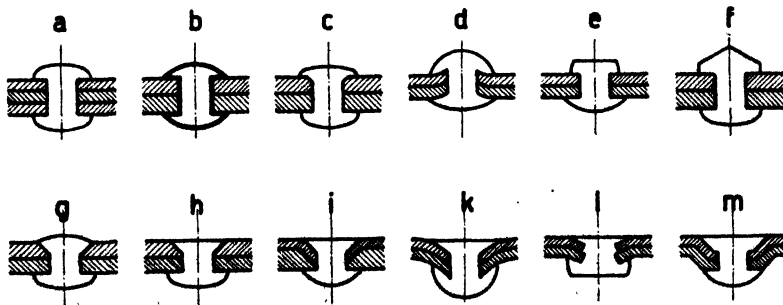


Fig. 380. Rivet shapes.

- |                                     |                           |                       |
|-------------------------------------|---------------------------|-----------------------|
| a. Snap head (elliptical)           | e. Pan head (hammer head) | i. Dished countersunk |
| b. Clad rivet                       | f. Conical head           | k. Dimpled mushroom   |
| c. Half countersunk                 | g. Countersunk            | l. Dished pan head    |
| d. Round or mushroom head (Dornier) | h. Flush countersunk      | m. Debergue rivet     |



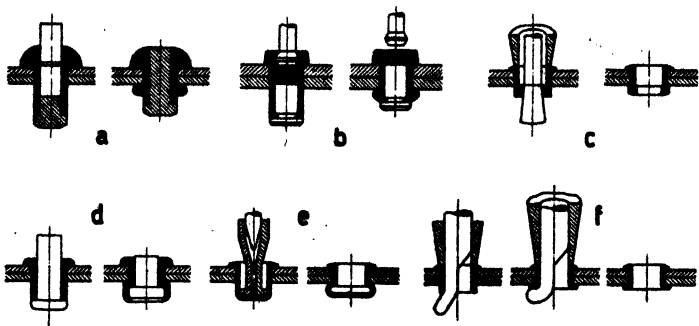


Fig. 381. Special rivets for heading from one side without a holding-up dolly.  
a. and b Huck rivet; c. Chobert rivet; d. and e. Junkers rivet f. Breguet rivet.

head in various materials with a rivet diameter of 10 mm (.393 inch). The smaller force required by the pan and conical heads compared with the round and elliptical heads is clearly to be seen. Special rivets for heading from one side only (Fig. 381) and explosion rivets Fig. 382) are dealt with below.

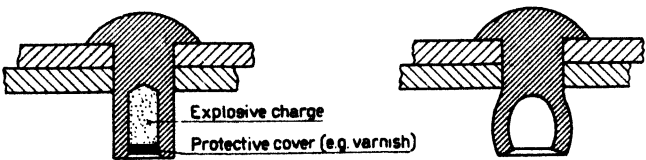


Fig. 382. Explosion rivet, before and after explosion.

TABLE 57

WORK IN FOOT POUNDS REQUIRED FOR FORMING THE HEADS OF RIVETS  
10mm DIAMETER (.393 INCH)

Material	Shape of head			
	Pan	Flat cone	Half round	Elliptical
Pure Al, half-hard . . . . .	65	72	123	130
Anticorodal (Al-Si-Mg) Rivet quality . . . . .	190	230	310	330
Avional or Duralumin (Al-Cu- Mg), freshly quenched . . . .	250	300	410	470
Peraluman3 (Al-3Mg) . . . . .	170	220	330	380
Peraluman5 (Al-5Mg) . . . . .	220	280	440	490

4. RIVETING PRACTICE

As light metal rivets transmit load solely through bearing pressure and shear stress, the use of such rivets calls for higher accuracy than hot driven steel rivets. The diameters of rivet shank and rivet hole must be accurate to prescribed tolerances, as in Table 58. Owing to the notch sensitivity of light alloys, the edges of the rivet hole should be slightly

chamfered (Fig. 383). As the larger size rivet holes cannot be drilled accurately enough to diameter, these should be drilled undersize and reamed out to size. Fig. 385, B, shows how the rivet is first upset with a hammer until the shank completely fills the hole, and then the head is finished to shape with a snap. With rivets of  $\frac{1}{2}$  inch diameter and over, it is advisable to use the cross-ribbed snap for forming shaped heads, as shown in Fig. 384, with a rotating air hammer. The forming of pan or cone heads is simpler.

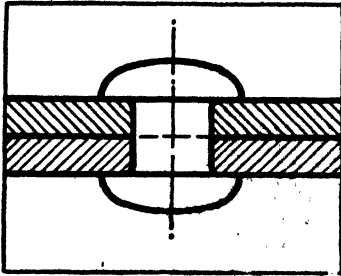


Fig. 383. Rivet with slight chamfer.



Fig. 384. Cross-ribbed rivet snap.

TABLE 58

DIAMETERS OF RIVET HOLES AND RIVETS FOR LIGHT METAL JOINTS

Rivet		Rivet hole		Rivet wire *		Rivet shank at head *		Rivet shank at end *	
mm	in	mm	in	mm	in	mm	in	mm	in
2.5	.098	2.6	.102	2.4	.094	2.5	.098	2.4	.094
3.0	.118	3.1	.122	2.9	.114	3.0	.118	2.9	.114
3.5	.138	3.6	.144	3.4	.134	3.5	.138	3.4	.134
4.0	.158	4.1	.161	3.9	.154	4.0	.158	3.9	.154
5.0	.197	5.1	.201	4.9	.193	5.0	.197	4.9	.193
6.0	.236	6.1	.240	5.9	.232	6.0	.236	5.9	.232
7.0	.276	7.1	.280	6.9	.272	7.0	.276	6.9	.272
8.0	.315	8.1	.319	7.9	.311	8.0	.315	7.9	.311
10.0	.393	10.1	.398	9.9	.390	10.0	.393	9.9	.390

\* Tolerance:  $\pm 0.05$  mm,  $\pm .002$  inch

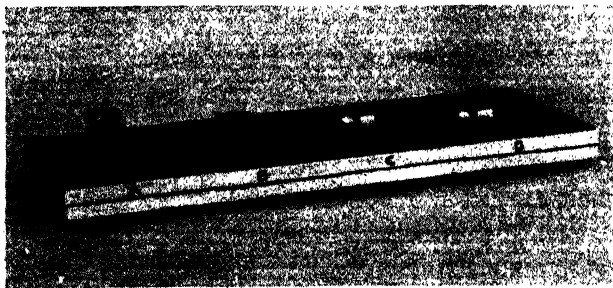


Fig. 385. Steps in driving a rivet.

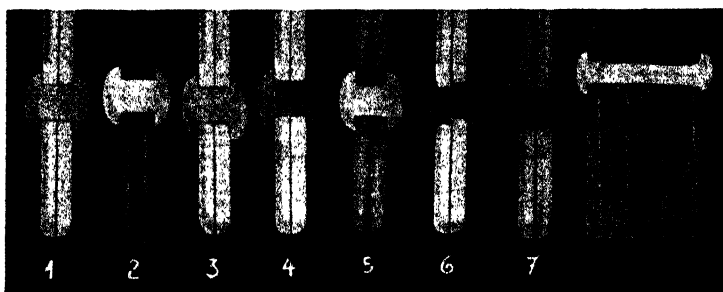


Fig. 386. Correct and incorrect driving of rivets.

- |                           |                            |                               |
|---------------------------|----------------------------|-------------------------------|
| 1 Correctly driven rivet. | 4 Shank length too great.  | 7 Sheets not properly gripped |
| 2 Small chamfer omitted.  | 5 Shank length too small.  | together by rivet.            |
| 3 Driven head displaced.  | 6 Rivet holes out of line. | 8 Rivet shank too slender.    |

Some of the many faults which may occur in riveting are shown in Fig. 386.

For very highly stressed rivets, it is advisable to increase the shear strength by incorporating a steel liner, which may be a split one. As this is protected by the rivet heads against the ingress of moisture, there is no risk of corrosion with this. In riveting aluminium and steel parts together, steel rivets are generally used, which, on the light metal side, are provided with washers of heat-treated light alloy or cadmium coated steel. It is also advisable to apply a coat of paint to give additional protection against corrosion. Owing to the high thermal conductivity of aluminium alloys, steel rivets may even be driven hot through light metal members.



Fig. 387. Light metal rivets with steel sleeves.

## 5. ONE-SIDE RIVETING

Riveting has sometimes to be done on parts accessible from one side only, and this happens not only in repair work on aircraft and land vehicles but also in their construction. The first example of this type of riveting was a tubular framework with a stressed light metal outer skin which as long as 20 years ago was riveted with the Junkers inside riveting dolly with spring studs shown in Fig. 388. In other cases where access is available

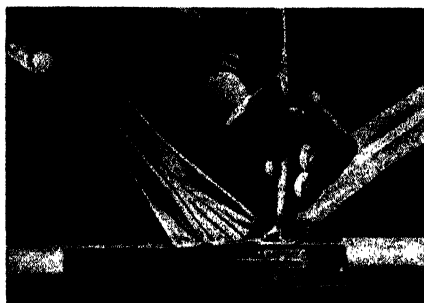


Fig. 388. Tool for inside riveting (Junkers).

from one side only, the types of rivet shown in Fig. 381 are used, in which a heading piece or expanding tool is always passed through the hollow rivet. The holding-down tool on the outside then presses the rivet head against the sheet and the shank of the inserted heading or expanding tool is drawn towards the outside whereby the closing head is formed. The principles of the various methods can be seen in the illustration. This

type of rivet is widely used in steel as well as in light metal construction, but has the disadvantage that the hollow rivets have an appreciably smaller shear strength than solid ones. Huck, among others, has developed the retention of a bolt in the rivet after completion of the heading operation which increases the shear strength of the rivet. By this method, the mechanical efficiency of riveted joints of this type is much increased. This type of riveting is quite expensive and also has the disadvantage that in closing the rivet, the compression of the shank in the rivet hole is insufficient to ensure a good bearing pressure. A further disadvantage of rivets of this type is that they are not fluid-tight.

The explosion method of riveting has been recently introduced, credit for the invention going to the BUTTER brothers. The chief difficulty is in the detonation of the rivet, and what is required is a propellant explosive which will detonate on heating to  $130^{\circ}$  to  $150^{\circ}\text{C}$  ( $266^{\circ}$  to  $302^{\circ}\text{F}$ ). The explosive and the gases from it should not have a corrosive effect on the material of the rivet nor that of the aircraft. Neither should the gases from the explosive have any noxious effect on the health of the work-people, otherwise the application of this method would be very difficult. All that is required in carrying out this method is to apply a hot iron to the head of the rivet after it has been inserted in the rivet hole to heat the rivet to  $150^{\circ}\text{C}$  ( $302^{\circ}\text{F}$ ), when the explosive will detonate. To make explosive rivets, the rivet shank is bored from the closing end, as in Fig. 382, the diameter of the bore being half that of the shank. The bore is filled three quarters full of the explosive which is compacted under light pressure, and to protect the charge from damp and to prevent it from coming out, the bore is sealed with a special varnish. The detonation of the charge not only causes the shank to bulge and form a head on the rivet, but also compresses the shank in the rivet hole. Naturally this compression is not so much as when the rivet is driven mechanically in the ordinary manner, and it is therefore necessary that, with the explosive

method, the rivet must be drilled very accurately to size, giving close limits of clearance between the rivet hole and rivet shank of .002 to .004 inch. Attention to this will ensure that the rivet shank fills the rivet hole completely, with some bearing pressure on the walls even when not under load.

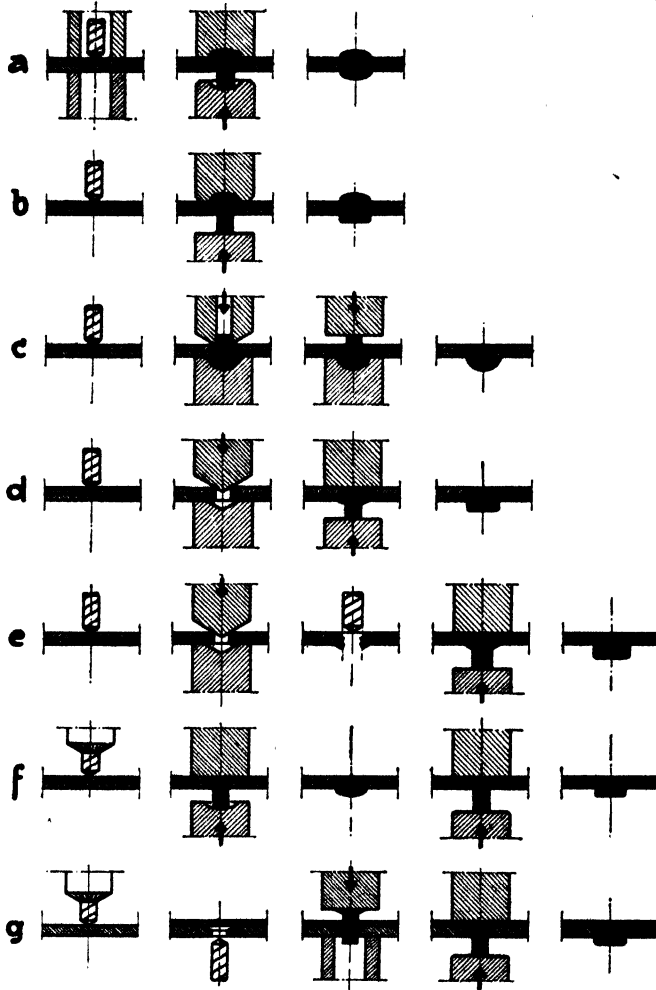


Fig. 389. Different types of machine riveting. (C. H. Flock)

## 6. MACHINE RIVETING

The high labour cost of riveting had, as early as 1937, shown the need for mechanising the work as far as possible. The considerable diversity of riveting operations that may have to be provided for is illustrated in Fig. 389 a to g. For simple half round rivet heads, the following is the general sequence of operations: drill, ream and lightly chamfer, insert the rivet,

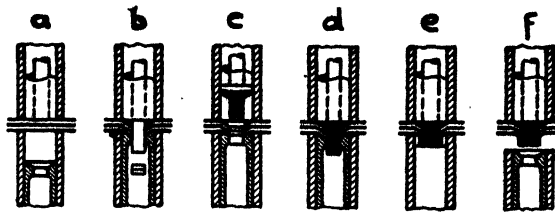


Fig. 390. Explanatory diagrams of automatic riveting according to VDI-Zeitschrift, (Verein deutscher Ingenieure Z = German Engineering Association Journal.) 1940, p. 914.

- a) Clamping the sheets between upper pressure head and lower clamping quill.
- b) Indenting the sheet for a countersunk rivet, stamping the sheet on the die head, then punching the hole.
- c) Inserting the rivet in the upper pressure head
- d) Inserting the rivet into the hole
- e) Compressing the shank
- f) Slacking back the lower clamp ready to move the sheet along.

strike or squeeze same; with countersunk rivets, the countersinking of the rivet hole (Fig. 389 f & g) or the indenting of the sheet as variously shown in Fig. 389 c, d & e, are the methods in use. It is to be noted that the clamping together of the sheets to be riveted by a riveting clamp is desirable for the best work and should be provided in a first class riveting machine. This is only shown in Fig. 389 g.

For closing the head of the rivet, either striking or squeezing is used, and for the former there can be single stroke or automatic multi-stroke hammers. Today squeeze riveting is used not only because of the superior shape of rivet head formed, but also because it has the advantage of eliminating the objectionable noise of the riveting hammer, which is a particular nuisance in large factories. In flush riveting, in which according to the system adopted either the manufactured head (Fig. 389 d) or the closing head (Fig. 389 c) may be countersunk, heading is generally done from the interior of the aircraft. The flat or pan head (Fig. 389 b) has been used in America for some time for economy in time and tools. The types of rivet shown in Fig. 389 c, d, e and g with indented or dimpled rivet holes must be mentioned, as these permit of a greater transfer of force between the sheets than the non-countersunk rivets such as in Fig. a, b and f. Furthermore the unreamed rivet holes which have a stepped bore after indenting (Fig. 389 c, d and g) are not so good as the reamed smooth holes (Fig. 389 e), and for high quality work, the latter more complicated method is necessary.

Machines were originally developed which automatically carried out the drilling, reaming and chamfering of the rivet holes, with automatic removal of the drilling swarf. Punching was sometimes substituted for drilling but this was not found to be so good as drilling, as cracks were sometimes formed around the hole and caused stress concentrations. A further step is the automatic indenting of the lip of the hole and finally the automatic insertion of the rivet and heading it by hammering or pressing.

In the simpler riveting machines only the insertion and heading of the rivets is done automatically. Fig. 390 a—f shows the operations in a fully automatic machine, in which stamping of the hole to shape, punching, it, the insertion of the rivet and the forming of the rivet head are all included. Fig. 391 shows a full view of an automatic riveting machine by the F.M.A., which drives 15 to 20 rivets a minute.

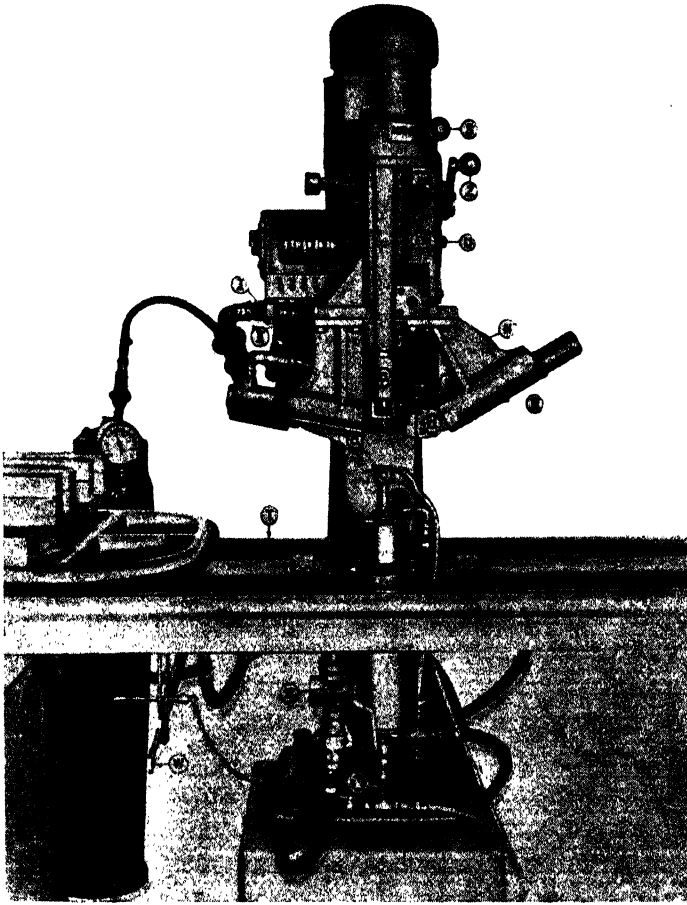


Fig. 391.

Full view of NA4 automatic riveting machine by the Frankfurter Maschinenbau AG.

- |   |   |     |   |
|---|---|-----|---|
| S | = Master switch                                       | II  | = Compressed air valve (Rivet magazine)   |
| Z | = Intermediate switch                                 |     | (Chip blower on top of work)              |
| O | = Neutral   | III | = Valve for 60 mm stroke of riveting head |
| U | = Socket for key for turning the machine over by hand | IV  | = Valve for riveting hammer               |
| a | = Drill and drill clamp for the sheet                 | V   | = Throttle valve for hammer               |
| b | = Sheet clamping quill for riveting                   | VI  | = Valve for shifting rivet magazine       |
| c | = Holding up tool                                     |     | Compressed air hoses:                     |
| d | = Rivet feed  | G-G | = For holding-up tool c                   |
| n | = Rivet shear   | H-H | = For hammer                              |
| M | = Nut for vertical adjustment of riveting head        | B-B | = For sheer clamp b                       |
| T | = Work feed table                                     | A-A | = For taking off                          |
| W | = Elevating lever for feed table                      | N-N | = For rivet feed                          |
|   | = Main air valve                                      |     |   |

## CHAPTER XVII: SURFACE TREATMENT

### 1. GENERAL

The condition of the surface of aluminium is a determining factor in a number of its properties. Thus the value of the corrosion resistance, fatigue resistance, single and reversed bending, frictional and reflecting properties, depend to a great extent on the condition of the surface of the metal. The surface varies considerably according to the method of manufacture. Rolled and extruded products, have the smoothest surface. Then come hammered and drop forgings, and lastly castings, ranging from pressure or gravity die castings to sand castings which are the roughest of all. In heat-treatment, the natural oxide film 0.000002 inch thick be-

TABLE 59  
GRAIN SIZES OF POLISHING GRITS AND POWDERS  
(GERMAN ENGINEERING SPECIFICATION DIN 1171)

Grain size	Meshes per inch, U.S.A.	Designation of sieve = width of mesh apertures	Wire diameter	Meshes per cm. old designation	Use
1	2	3	4	5	
10/0 9/0	400 320				Polishing
8/0 7/0 6/0 5/0 4/0	280 240 220 180 150	0.060 mm 0.075 0.090 0.100	0.040 mm 0.050 0.055 0.065	100 80 70 60	Fine grinding
2/0 0 1 3	120 100 80 60	0.12 0.15 0.20 0.25	0.08 0.10 0.13 0.17	50 40 30 24	Grinding
5 6 8	50 40 36	0.3 0.4 (0.43)	0.2 0.24 (0.28)	20 16 (14)	Rough grinding with hard bobs
9 10 11 14	30 24 16 20	0.5 0.6 0.75 1.0	0.34 0.4 0.5 0.65	12 10 8 6	Rough grinding with vitrified emery wheels



comes thicker and after heat-treatment at a temperature of 500°C (932°F) increases to 0.000008 inch. In magnesium-bearing alloys, the film is composed not only of aluminium oxide, but also of magnesium nitride, which causes a typical rather dark flecked appearance. The thickest oxide skin is found on castings.

The principal processes of surface treatment are;

*Rough grinding, dressing or snagging*: The smoothing down of rough portions of surfaces of drop forgings and castings, and the stubs left on castings by sawing off risers and gates, using coarse emery wheels or steel rasping or snagging wheels.

*Grinding, or cutting down*: Done with emery grit of grain size 60 to 120.\*

*Fine grinding, glazing or oiling*: Done with 150 to 280 grit with grease.

*Long grinding*: Fine grinding with a parallel movement of the buff, leaving the fine scratches running in one direction.

*Polishing*: Production of a mirror like surface finish by the use of a loose mop with application of a grease polishing composition.

*Colouring*: Final polishing with very soft swansdown or chamois leather mop, generally with some application of a suitable polishing paste.

*Matt finishing*: Production of a smooth semi-lustrous matt finish by means of a fibre or horsehair brush with application of a polishing composition.

*Tumbling*: Production of a high burnished finish on quantities of small articles by tumbling them with steel balls and soap suds in a tumbling barrel.

*Scratch brushing or satin finishing*: Treatment with fine wire revolving steel brushes, giving a silvery white satin-like surface.

*Graining*: Shaking with balls, gives a uniform matt surface.

*Decorative grinding*: Decoration of the surface by a systematic arrangement of circular or straight grinding patterns, the "engine turned" finish being of this type. Engraving with sharp tools also belongs to this class of finishing.

*Hand rubbing*: Rubbing by hand with steel wool, or hand scouring with powder, paste or liquid scouring agents.

*Hammering*: Indenting of the surface with a rounded ball shaped tool.

*Sand-blasting*: A matt surface produced by the impingement of silica sand by a compressed air jet.

*Chemical oxidation*: The natural oxide film is thickened up by immersion in an oxidising bath.

*Electrochemical oxidation*: In this process the oxide film is thickened by electrochemical treatment, with the light metal connected as the anode. The process is for this reason called "anodic oxidation". It produces the thickest oxide film.

\* American designation — Table 59 col. 2.

## 2. MECHANICAL SURFACE TREATMENT

The mechanical surface treatment of the light metals is very similar to that of heavy metals and therefore does not need to be explained in full detail. It is of prime importance that perfectly clean appliances are used as all contamination of the surface by foreign metals is to be avoided. As in the case of machining, the highest speeds give best results in grinding and polishing aluminium, and these conditions should always be aimed at. The work tends to heat up rather excessively under these conditions, so that cooling must be allowed, either by dipping in a cold liquid or by changing the pieces frequently. The schedule of operations depends on the original surface condition of the piece. The worse this is, the greater number of preliminary operations are necessary. With better surfaces to start with, the preliminary operations can be reduced. A cardinal principle in grinding and polishing is that succeeding operations should always put on scratches in a direction transverse to the preceding operation and should be continued for a sufficient length of time to remove completely all traces of the preceding operation.

### a. *Rough grinding, dressing or snagging*

This operation is generally used on castings and is frequently required on forgings. In either case, revolving milling cutters, rasping wheels or emery wheels of 16 to 60 grit are used. The last named load up rather quickly with aluminium. Resin bound wheels with a finer grit have an advantage of wearing down more quickly and thus exposing fresh grains at the surface for cutting. Vitrified wheels on the other hand have a longer life. The allowable speed is 3500 to 7000 feet per minute, and protection against bursting of wheels should always be provided.

### b. *Grinding*

Grinding is done in two degrees of fineness, i.e., grinding, and fine grinding, glazing or oiling. The grit used is artificial emery and this must have a uniform grain size. The grinding grit is either applied to an emery band, or is glued on felt, chrome leather, wood, or metal bobs. When worn, the old grit should be completely removed from the surface before new grit is applied.

For the coarse stage of grinding, a grit of 60 to 120 is suitable and 150 to 280 for fine grinding, the peripheral grinding speed being 6000 to 7500 feet per minute. Some various types of grinding machine are shown in Fig. 392. Rubber rings with an endless emery band drawn on to them are much in use. Centrifugal force causes the rubber to expand outwardly,



Fig. 392. Grinding and polishing machines.

Upperleft : Tumbling barrel.  
Lower left : Belt grinder.

Right : Various power operated  
hand grinders.

thus tightening the emery band. Tallow, suet or paraffin are used as lubricants. Grinding compositions containing the necessary grinding agent and lubricating medium are convenient to use.

### c. *Polishing*

The capacity for taking a polish depends less on the hardness of the material polished than on the fineness and uniformity of the grit of the polishing agent. For high lustre, a careful preparation by coarse and fine grinding is imperative. For polishing, loose mops of close textured cotton, up to 13 inches diameter and  $1\frac{1}{2}$  inches wide, are used, running at a speed of up to 11,000 feet per minute. The polishing agent may consist of a composition paste of finely ground alumina or green chrome powder mixed with stearine and wax as binder, the colour of the paste being discernible in the polished surface. As the pieces warm up in polishing, the recommendations given earlier in this section for grinding should be followed. Polishing is best done in a direction transverse to that of the preceding operation.

### d. *Colouring or fine polishing*

After the polishing operation there may follow a fine polishing or colouring operation, after the residual traces of polishing compo have firstly been removed by rubbing with a soft wool cloth dampened with a mixture of equal parts of benzine and petrol. For the colouring, loose wool, swans-

down or chamois leather mops are used, with an application of Vienna lime, alumina or rouge compo. Aluminium is not often subjected to this operation however, as the standard polishing gives a very high lustre.

e. *Matt finishing*

By buffing the glazed surface in the direction of glazing with a fibre or horse hair brush, a metallic semi-lustrous matt finish with uniform parallel scratches is obtained. The advantage of this finish is a diffuse reflectivity which makes the surface look white. This finish is used considerably in fittings of buildings and can be subsequently reconditioned by rubbing with abrasive cloth. A composition of alumina or very fine emery of 220 to 280 grit with beef tallow is applied as the finishing medium.

f. *Ball burnishing*

Ball burnishing is a mass production process. Rough parts must first be fine ground, while clean smooth parts need only be dipped in hot 10% caustic soda liquor. Copper-bearing alloys must be dipped after soda treatment in a solution of 1 part strong nitric acid and 1 part water. A six-sided or eight-sided tumbling barrel (Fig. 392, upper left) is charged with steel balls  $\frac{3}{32}$  to  $\frac{1}{4}$  inch diameter, and soap suds made with about  $\frac{1}{2}$  pound of soap flakes or hard soap to 20 gallons of water, together with the articles to be burnished, and is rotated at 15 to 50 r.p.m. according to its diameter. The tumbling lasts for  $\frac{1}{2}$  to  $1\frac{1}{2}$  hours depending on the quality of finish desired. The barrel is completely emptied after each charge has been tumbled, the suds is renewed and the balls are washed clean of polishing sludge with water. Sometimes the balls are dipped in soda liquor to remove adhering aluminium. The articles may be given a final polishing in a second barrel with leather clippings, which improves the lustre considerably.

g. *Scratch brushing, Satin finishing*

A matt surface which is particularly suitable for taking coatings is obtained by scratch-brushing with revolving steel wire brushes. The crimped steel wire bristles are .0025 to .010 inch diameter, their length is  $1\frac{1}{4}$  to 2 inches and the peripheral speed of the brush is 1800 feet per minute. The rate of feed of the work is about 3 feet per minute, and the pressure of the brush is quite light. Before brushing, the surface is thoroughly degreased. Also, each place should only be brushed once, otherwise the effect will not be uniform. Scratch brushed surfaces are more liable to corrosion than smooth surfaces, owing to their slight roughness, and they should therefore have some protective treatment.

#### *h. Graining*

This process is applied to flat sheets. The sheet to be grained is clamped in a frame which can be set in vibratory motion by an eccentric mechanism. The sheet to be grained is covered with a quantity of steel balls, 1/8 to 3/8 inch diameter, (or wood balls are sometimes used) and a grinding medium. The operation takes a quarter of an hour. A fine texture of surface somewhat similar to a sand blasted surface is obtained.

The processes of decorative grinding, hand rubbing, hammer-finishing, and sand-blasting follow similar lines as with other metals, and therefore will not be described in further detail.

### 3. CHEMICAL SURFACE TREATMENTS

#### *a. Pickling or dipping*

Aluminium and its alloys can be treated in acid or alkaline baths. It is important that the attack by the bath shall be uniform all over the surface. Some baths tend to give a preferential attack at the grain boundaries, which reduces the mechanical properties, especially the fatigue strength. In alkaline baths, any heavy metals present in the alloy, such as copper for instance, remain undissolved on the surface as a dark residue.

The usual pickling liquid is a 10% to 20% caustic soda solution, which at 50°C to 80°C (122° to 176°F) will have exerted a sufficient effect in 1 to 2 minutes. The best practice is to lift the material from the soda bath after one minute, rinse it in running water and redip in the soda for a further minute. After this, the material must be thoroughly rinsed in order to remove any traces of soda, which would be detrimental. With alloys containing heavy metal constituents, a subsequent dip in 10% nitric acid is essential, and indeed this is advantageous also for pure aluminium and alloys free from heavy metals, in order to assure neutralisation of the soda.

To give a dead white surface, a cold bath made up of equal parts of conc. nitric acid and a saturated solution of sodium fluoride is used. This must be held in a hard rubber or stoneware vessel. The time required in the liquor is 2 to 5 minutes.

#### *b. Etching*

For deep etching designs or inscriptions in the surface of the metal, the following solution is used:

- 2 parts 10% chloride of iron
- 2 parts 10% chloride of copper
- 1 part conc. nitric acid
- 2 to 6 parts denatured alcohol

The greater the alcohol content, the slower is the etching action. Those parts of the aluminium which it is desired not to etch are covered with a "resist" composed of a resistant asphaltic varnish, which is dissolved off in benzene after the etching of the uncoated portions has been completed.

#### 4. OXIDE COATINGS

##### a. Introduction

In the presence of air, aluminium alloys acquire a thin, dense, resistant, but transparent oxide skin, which effectively protects the underlying metal from corrosive attack. The oxide film of the coating may be of different thicknesses according to the conditions under which it is formed. The thickness may be much increased by chemical and electrochemical methods. The following table gives the thickness of oxide coating formed under various conditions:

TABLE 60  
THICKNESS OF OXIDE FILM ON ALUMINIUM

Natural oxide skin on cut surface (1 to 6 months old) . . .		.000002 in.
After annealing at 600°C (1112°F) for 80 hrs . . . . .		.000008 in.
Solidified from the molten state . . . . .		.000016 in.
MBV coating . . . . .	.00004 to	.00008 in.
Anodic coating . . . . .	.0004 to	.0016 in.

##### b. Chemical oxidation processes

In chemical oxidation processes, oxidising liquids in which the material is treated, cause an increase in thickness of oxide film. The M.B.V. (modified BAUER-VOGEL) process is the best known example of this type. In this process, a solution containing 5% of soda ash or 13% soda crystals, plus 1.5% sodium chromate is used at a temperature of 90 to 96°C (194 to 205°F). The time of treatment is 5 to 10 minutes. The consumption of solution is about 1 gallon per 150 square feet of aluminium surface. With the addition of 0.25% caustic soda, the process can be carried out cold.

In the case of heat-treated alloys, a preliminary pickling is recommended. Pure aluminium and alloys low in magnesium acquire a grey matt oxide surface, while with increasing magnesium the oxide film becomes completely colourless. Subsequent boiling in water or 2% water-glass solution

appreciably improves the protective effect of the MBV film. When it is intended for a base for paint, it is of advantage to bake the articles at 95° to 100°C (203° to 212°F) and they should not be handled before painting.

Developments of the MBV process are found in the EW and LW processes. In the former, the MBV bath has 0.1 to 0.2% by volume of water-glass added, while in the LW process, 5 ozs. per gallon of disodium hydrogen phosphate ( $\text{Na}_2\text{HPO}_4 \cdot 12\text{H}_2\text{O}$ ) are added. These processes give coatings of greater thickness and smoothness, but they are not suitable for taking paint.

### c. Anodic or electrochemical oxidation

#### i. General

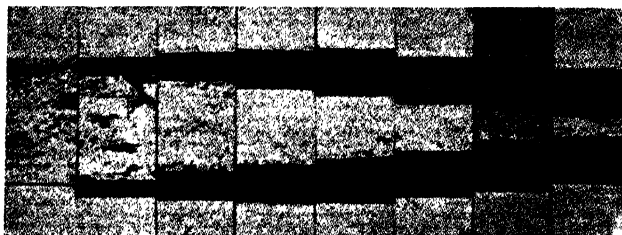
The thickest oxide films are formed by anodic oxidation and these may attain a thickness of .01 mm to a maximum of .04 mm (.0004 to .0016 inch) according to the particular process and duration of treatment. Buff in 1857 was the first to recognise the electro-chemical formation of a thickened oxide coating, but it was Bengough and Stuart in 1923 who were the first to introduce anodic oxidation as a commercial process for surface protection in aircraft manufacture in England. Since then a great number of different processes have been developed and are known under trade-marked names such as Alumilite, Anodal, Anoxal, Eloxal, Ematal, Alzak, Brytal etc.

In the anodic oxidation process, the oxide and hydroxide coating is formed from the aluminium itself and is therefore firmly attached to it. There is a slight increase in size due to the increased volume of the oxide, but this only amounts to 1/3 of the thickness of the oxide film. With films of increasing thickness, a chemical dissolution of the oxide film in

Investment

Foil thickness

Investment



Duration of oxidation	0	30	60	90	120	150	180	210	Min
Film thickness $\mu = .001 \text{ mm}$	0	14	26	37	43	43	43	43	$\mu$
Change of weight	0	+100	+174	+198	+40	-108	-270	-429	$\text{mg/dm}^2$
Change of thickness	0	+11	19	+27	+29	+20	+7	-5	$\mu$

Fig. 393. Effect of duration of anodic oxidation on thickness of film.

the electrolyte begins to take place, which counteracts the growth. Fig. 393 shows the effect of the duration of oxidation on the film thickness and on the overall thickness, the oxide film being coloured dark.

The oxide film may be corundum-hard, dense and brittle; or soft, porous and elastic, according to the current density, temperature and duration of treatment. As the underlying metal is soft, the anodic layer can be cut through by sharp objects. The hard coatings have an elongation of 2 or 3% only, and thus fine hair cracks are formed if the article is stretched to a sufficient extent.

The most outstanding characteristic of anodic coatings is the effective surface protection which they afford. A newly formed coating has an appreciable porosity, which can be eliminated by an after-treatment, known as sealing. The greatest corrosion protection is obtained by impregnating the coating with synthetic resin. Sealing increases the electrical insulation resistance considerably, and this may attain a breakdown strength of up to 1000 volts. Coatings in the porous condition are very absorbent and can be coloured with inorganic and organic dyes. The lightest coloured coatings are formed on pure aluminium and on Al-Mg alloys, such as Peraluman, while the alloys containing heavy metals give darker coatings. In suitable anodic baths, coloured coatings may be produced, gold coloured for instance. The heavy-metal-containing alloys may give streaky coatings due to segregation, which detract from the good appearance of the coating. Surface defects are not eliminated by anodic oxidation and consequently these should be removed beforehand by grinding and polishing. Special anodic processes, i.e. the electrolytic brightening processes, give highly reflective surfaces, which are used as mirrors or reflectors.

As the aluminium is connected as the anode, no other metal, which may go into solution at the anode, may be in contact with the electrolyte. If it is not possible to remove any such metallic attachments from the aluminium article before anodising, the foreign metal must be coated beforehand with an insulating varnish. Also local heating, which alters the structure, will result in a local difference in colour in the coating, as may be found in welded joints for instance. Heavy metal solders must be varnished beforehand as they contain foreign metals. Riveted joints in pure aluminium or Peraluman (Al-Mg alloy) are not affected with colour differences.

#### ii. *Commercial anodic processes*

The processes given in Table 61 below are employed in commerce :



TABLE 61

## ANODIC PROCESSES

GS*	process	Direct current in sulphuric acid.
GX	process	Direct current in oxalic acid at 20°C (68°F).
GXh	process	Direct current in oxalic acid at 35°C (95°F); gives clear coatings.
WX	process	Alternating current in oxalic acid.
WGX	process	Alternating superimposed on direct current in oxalic acid.

The cheapest and the most widely used is the American direct current sulphuric acid process (GS).

The GS process: This goes under the trade name Alumilite and is a direct current process using an electrolyte of dilute sulphuric acid to which additions such as glycerine, chromate, and sulphate etc. may be made. The properties of the anodic oxide coating vary according to the working conditions (concentration of sulphuric acid 5 to 70%, temperature 10° to 30°C, 50° to 86°F, current density 5 to 30 amps/sq. ft, time of treatment 10—30 mins.).

The hardest coatings are obtained with the lowest concentration of acid in the electrolyte and at the lowest temperatures; coatings of high absorbent quality suitable for dying with colours are obtained in 20 to 30% acid at about 25°C (77°F). Usual conditions are 20—30% sulphuric acid at 20°C (68°F) with 15 to 20 amps/sq. ft, and with a time of 30 to 45 minutes. The voltage, according to the material and method of operation, runs from 10 to 25 volts. The energy consumption is from .05 to .2 KWH per sq.ft.

GX and GXh processes: These are direct current oxalic acid processes with an electrolyte of 2 to 12% oxalic acid with different additions such as chromates, permanganates, sulphates etc. At ordinary temperatures of working (GX), the voltage across the bath for the required current density of about 15 amps/sq. ft is about 60 volts, and the consumption of energy is correspondingly high, namely .6 to .8 KWH per sq. ft. A temperature of 35 C (95 F) is maintained in the GXh process, at which the voltage required is only 30 to 50 volts.

The GX process gives extremely hard yellow coatings on pure aluminium and magnesium-bearing alloys. It is particularly suitable for the treatment of surfaces which have to work under conditions of sliding friction. The GXh coatings are light coloured on pure aluminium and heavy-metal-free alloys, are softer than the GX coatings and are suitable for dyeing.

WX and WGX processes: The WX process is carried out with alternating current with increasing voltage from about 20 volts rising to 60 volts at room temperature. The WX coatings are softer than those described above.

\* The initials are from German words. G, Gleichstrom = Direct current. W, Wechselstrom = Alternating current. S, Schwefel = sulphur. X, Oxal- = oxalic. h, heiss = hot.

If flexible oxide coatings are required, as on wires and strips for example, the temperature of the bath is increased to 40° to 45°C (104° to 113°F), under which condition an alternating current voltage of 30 to 40 volts is sufficient. For service requiring greater hardness and corrosion resistance, the WX process is combined with the GX, the initial stage of oxidation being carried out with alternating current and the final stage with direct current.

The original process as invented by Bengough and Stuart, in which oxidation is carried out in a 3% chromic acid solution, has the disadvantages of the emission of a noxious vapour and of a voltage rise of 5 to 50 volts as oxidation proceeds. The time of treatment is 40 to 50 minutes and the energy consumption, by reason of the high voltage, is about 0.2 KWH per sq. foot of anodised surface. Nevertheless the coating is always less than 0.0004 inch in thickness.

In the Ematal \* process, a white pigment, titanium oxide being used for preference, is incorporated with the oxide coating as it is formed, and by this method an opaque, porcelain-like coating of superior hardness and resistance is formed.

For bright oxide coatings, the Alzak \* and Brytal \* processes are in use. These produce glass-clear, hard oxide coatings with a high reflecting power and high permanence even in damp atmospheres. To begin with, the mechanically polished surface is anodically brightened in an electrolytic brightening bath, while in a second bath, a thin glass-clear protective oxide film is formed, which prevents the mirror-like surface from becoming tarnished.

In the American Alzak \* process, the brightening treatment is done in a sulphuric-hydrofluoric acid electrolyte at room temperature with direct current, then follows the protective film formation by the direct current sulphuric acid process.

In the British Brytal process, the brightening is carried out in an aqueous solution of 15 %  $\text{Na}_2\text{CO}_3$  + 5 %  $\text{Na}_3\text{PO}_4$ . Following this, the oxide film formation is carried out in a 20%  $\text{NaHSO}_4$  solution at 35°C (95°F).

The reflecting power of the brightened oxide films diminishes as the purity of the metal falls, so that for the production of mirrors and reflectors, super purity aluminium or Raffinal \* of over 99.99% purity is used.

To counteract the extreme softness of this material, a small addition of magnesium may be used without detrimental effect on the reflectivity, as in the alloy Reflectal \*. Some use is also made of commercial pure aluminium or aluminium alloys clad with super purity aluminium (Raffinal \*) or with Reflectal \*, especially in the manufacture of large reflectors.

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\* Registered trade-mark.

### iii. *Equipment for anodic plants*

The foregoing descriptions indicate that for the anodic oxidation of aluminium, beside an anodic bath, other baths are necessary for the prior and subsequent treatments, and to finish with there must be a washing tank.

For the prior treatment, the following are required: A sheet steel or aluminium hot degreasing tank containing P3 liquor (trisodium phosphate) or a sheet steel electrolytic degreasing tank; a sheet steel hot dip tank with 10% caustic soda solution; a stoneware or hardwood neutralising tank with nitric acid diluted 1:1; also to be recommended is a lead covered sheet steel or hard wood dipping tank with sulphuric-hydrofluoric acids, a nitric-hydrofluoric acid dip tank of iron or earthenware, with a vinyl resin or hard rubber covering in either case.

For the anodic process itself, at least one bath must be provided, but it is frequently more economical to work with baths of two or three different sizes. The tanks may be of hard wood, aluminium, or iron with lead covering, and must be equipped with cooling coils or cooling jackets, and provided with stirrers. The lead covering of the tank may if desired be used as the cathode.

Current may be supplied from a motor generator set with a direct current output voltage of 25 volts. Mercury arc rectifiers are not satisfactory for these low voltages. The current density is about 15 amps/sq. ft, which is equivalent to an energy consumption of 0.3 KWH/sq. ft. Thus for the anodic treatment of a sheet 6 ft.  $\times$  3 ft. in size, a 12 KW direct current generator is necessary. If several anodic tanks are installed, it is advantageous to have a plurality of small generators rather than one big machine.

It is also advisable to have a hardwood, enamelled iron, or aluminium hot water tank for the final treatment in boiling water.

For colouring the anodic coating with organic dyes, the general practice is to use water-soluble dyes in a concentration of 1 to 5 gm/litre (1 oz in 1—6 gallons). For the dyeing process, the still-wet articles are immersed in the hot dye solution at a temperature of 75°C (167°F) for 10—20 minutes.

The intensity of colour partly depends on the concentration of the dye bath, but more so on the thickness and degree of porosity of the anodic coating. Weak and cold dye solutions require a longer time for dyeing than hot strong solutions.

Colouring with inorganic colouring materials (Swiss patent 168,454) is a more complicated matter and one requiring greater practical experience than colouring in organic dye solutions.

The closing of the pores may be accomplished to a large extent by boiling the article in water for as little as 10 minutes. The coating swells somewhat

\* Registered trade-mark.

and becomes more dense. On prolonged standing in dry air, the swelling subsides to some extent.

A densening process that is without effect on the shade of the colour on colourless or dyed coatings is the acetate sealing process. This process makes use of a solution of 5.5 gm nickel acetate, 1 gm cobalt acetate and 8.5 gm boric acid per litre of water. The anodised and dyed articles are treated in this hot solution at 85°—95°C (185°—203°F) for 10—20 minutes. In this treatment, insoluble hydroxides are formed by hydrolysis from the soluble acetates and are preferentially precipitate in the pores, completely sealing them.

An after-treatment which greatly improves the highly porous coatings formed in the direct current anodic processes on high copper or silicon alloys such as Avional (Duralumin), Alufont, Silafont (Silumin), is bichromate sealing. In this treatment the pores are not filled up, but the exposed metal at the bottom of the pores is passivified.

Treatment of the coating with oils, fats or waxes closes the pores and renders the anodic coating water-repellent and corrosion resistant. For this treatment to be successful, the coating must be quite dry, otherwise unsightly blotches will appear. For wax impregnation, the anodised article which has had its coating densified in boiling water, then dried, is dipped for 30 minutes in a 5% solution of wax in turpentine at a temperature of 65°C (149°F).

The most effective corrosion protection is afforded by impregnation of the oxide coating with a synthetic resin. For this, the part, which may have been treated with bichromate sealing, is well dried and dipped in a very dilute synthetic resin solution and after draining is dried in hot air.

## 5. METALLIC COATINGS

Aluminium may be coated or plated with various metals either mechanically or electrochemically. There is no great commercial importance in these foreign-metal coatings. One application to be mentioned is armatures, on which a chromium coating is sometimes required, and in this the chrome plating of aluminium is not different from other armatures. The idea that such coatings provide a better corrosion resistance is generally erroneous, as the potential difference between the basis metal and the coating leads to an increased tendency to corrosion when the coating is porous, as it usually is. Some metals with baser potentials, such as zinc and cadmium, afford effective protection, however.

The simplest processes are those of chemical replacement, or metal dip processes, in which metals of more noble potentials than aluminium are precipitated by replacement, or "cemented", on to aluminium articles

immersed in suitable solutions of the metallic salts. As precipitation ceases as soon as the aluminium is coated with the foreign metal, only very thin weak coatings are obtained by this method, so that these processes are used mainly on account of the decorative effect obtainable. In addition, the dip process is convenient to use to give a base for electroplating.

For electroplating aluminium, a suitable surface treatment must first be carried out, to ensure a satisfactory keying of the electrodeposited coating to the aluminium. After a thorough degreasing, the aluminium surface is roughened by brushing, sand-blasting or chemical etching. If the coatings are to be finally polished, the basis metal must be polished to begin with, then only lightly but uniformly roughened as above. Etching with hydrochloric acid, hot iron and nickel chlorides, or alkaline zincates with hydrochloric acid additions, are used. Table 62 gives the composition of some etching baths.

TABLE 62

## ETCHING BATHS FOR PREPARATION FOR ELECTROPLATING

Material	Water	HCl (sp. gr. 1.18)	Metallic salt
Pure aluminium . . . . .	800 cc	90 cc	225 gm/litre $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$
All aluminium alloys, or second choice for pure aluminium . . . . .	800 cc	500 cc	3 gm/litre $\text{FeCl}_3$
	667 cc	333 cc	4 gm/litre $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$
	500 cc	500 cc	4 gm/litre $\text{MnSO}_4 \cdot 2\text{H}_2\text{O}$

The roughening can also be very well done by anodic oxidation, the anodic oxide coating being partly dissolved subsequently by being left in the bath without current. Nickel coatings adhere best to aluminium, so nickel plating is first carried out, for which suitable baths are given in Table 63.

TABLE 63

## NICKEL PLATING BATHS FOR ALUMINIUM

	Concentration gm/litre	
	I	II
Nickel sulphate crystals . . . . .	200	400—500
Nickel chloride . . . . .	25	22
Boric acid . . . . .	15	22
Sodium chloride . . . . .	5	—
pH (colorimetric) . . . . .	5.5—5.7	5.3—5.7
Temperature °C . . . . .	35—45	45—50
°F . . . . .	95—113	113—122
Current density, amps/sq. ft. . . . .	20—40	30—90

If the article is to be finished nickel plate, the nickel starting coat is copper plated, and this is followed by a bright nickel plate. In this way a sound, corrosion resisting plating is obtained.

A further process of metal covering is the metal spraying process originated by Schoop, by which zinc, lead or cadmium coats may be laid on aluminium. These sprayed coatings are always porous and require polishing to make them dense. The spraying of aluminium coatings on iron and steel is also now carried out. If super purity aluminium is sprayed on, lustrous coatings of high reflectivity and very good corrosion resistance are obtained by subsequent polishing, which are recommended as substitutes for nickel and chrome plating. As in the case of electroplating, the articles must be thoroughly clean and grease-free. If sprayed coatings are to be polished, the article must also be polished before spraying. In the case of aluminium alloy sheets, cladding by a rolling process is of widespread application for copper-containing alloys of the Duralumin type (Al-Cu-Mg) of somewhat inferior corrosion resistance, which are clad by this process with an outer layer of pure aluminium or a corrosion-resistant alloy. Finally, mild steel sheet can be coated with pure aluminium, whereby the resistance of this material to the effects of the weather is greatly increased.

## 6. PAINTING AND LACQUERING

Aluminium and its corrosion-resistant alloys exhibit a high resistance to the corrosive effects of the atmosphere, and aluminium overhead cables have stood up to urban atmospheres for 40 years and more. Nevertheless it is advisable that elements of structures, which may have to resist more corrosive conditions, are provided with some protection against corrosion. The most effective protection is by anodic oxidation, but this cannot always be applied to structural members owing to their size; for instance entire railway coaches cannot be anodised, so painting and varnishing are used in many cases. The greatest protection against corrosion is afforded by a combination of anodic coating and painting, the pores of the anodic coating giving a good hold to the paint.

Painting is done by ordinary methods, as for the heavy metals. As there is no rust penetration beneath the paint coat as occurs with steel, the life of paint on aluminium is much higher, and generally only a priming coat and a finishing coat are applied. To ensure good adherence for the priming coat, all grease must be thoroughly removed from the metal by one of the usual degreasing agents, and the surface must then be thoroughly dried. In degreasing, it must be remembered that even the best degreasing agents lose their effectiveness when they have taken up a certain amount of grease, so that a final wiping down with fresh grease-removing

solution and clean rags should be given. As the surface of light metal parts is usually smoother than in heavy metal structures, the preliminary filling and rubbing down is a less costly operation and may frequently be omitted altogether.

For the priming coat, any of the priming paints used for heavy metals are suitable for aluminium except those with a red or white lead pigment. The best primers for aluminium are synthetic resin varnishes and grease-insensitive nitrocellulose lacquers, the best of all being a synthetic resin with zinc chromate pigment. For the finishing coat, a stoving lacquer is frequently used. In the case of the natural-ageing Al-Cu-Mg (Duralumin type) alloys, a subsequent low-temperature heating to 100°C (212°F) adversely affects the corrosion resistance, so that with such alloys a lower stoving temperature must be used. In warm-ageing alloys, the stoving can be done coincidentally with the artificial ageing.

A very effective protection is given by the addition of aluminium powder to the finishing coat. In such an "aluminium paint", the high reflectivity of the outer layer of aluminium powder, which forms on the paint, protects the medium of the paint below it from the destructive effects of ultraviolet rays. A good aluminium paint may be mixed from 850 parts by weight of boiled linseed oil, parts 50 turpentine, and 300 parts by weight of aluminium bronze\* powder. The aluminium powder is put first in the receptacle, then the boiled linseed oil and finally the turpentine. After a thorough mixing, the paint is ready for use and it should not be ground as in the case of ordinary oil paints. During use, it is important that the aluminium powder is not allowed to settle to the bottom. For this reason, only enough paint should be mixed for one day's use. A dryer may be used in the first coat, but this should not be used in the second coat. By virtue of its high covering or hiding power, 1 lb of aluminium powder will cover 40 to 50 square feet of surface. Aluminium paint is also very good for the protection of wood, with a linseed oil varnish as a suitable primer. For heat-resisting paints for service up to 650°C (1202°F) aluminium powder is mixed with guaranteed acid-free bronze oil in the proportion of 1 to 2.

In America and England, aluminium powder is produced by some manufacturers in the form of aluminium paste, containing a proportion of grease. This aluminium paste has an advantage over dry powder in that it is dustless and more readily mixed into paint.

\* A designation of aluminium powder in the paint trade.

## CHAPTER XVIII: CONCLUSION

For the best adaptation of light metals to useful purposes, their particular technical qualities must always be given full consideration. The best results do not always follow from a simple replacement of the construction in exactly the same way as it was previously carried out in heavy metal. Rather than this, the conversion to light metal calls for an intelligent redesign on the lines of the principles laid down in the preceding chapters.

### 1. ECONOMIC CONSIDERATIONS

Beside those applications in which the metal is used on account of its decorative appearance, as for example in interior decoration and art ware, it is usually economic reasons that decide the application of aluminium, as determined by its low specific gravity, or in some cases by its high electrical or thermal conductivity, in others by its high reflectivity for light or radiant heat. In moving parts, weight saving is a most important factor, especially seeing that in many cases, beside the direct weight saving of the aluminium itself, this brings in its train other indirect savings of weight. For example, by using aluminium bogie frames in an electric tramcar, and so lightening them, it becomes possible to make the underframe lighter as well as the springs, the wheels, axles and bearings. In vehicle construction, the indirect weight saving is usually about 50% of the direct, while in marine construction, the indirect saving may be several times the direct. Experience has shown that in vehicle construction, the use of 100 lbs of aluminium will bring about a weight saving of 70 to 100 lbs. In Switzerland, the increased cost for the introduction of 100 lbs. of light metals instead of cast iron or steel formerly used would be equivalent to about 40 to 50 shillings sterling. It is not the price per pound of the light and heavy metals that should be used as the basis of comparison, but the price per unit volume, seeing that iron and steel are 2.8 times as heavy as aluminium.

The selection of alloy to suit the application is of importance. In many cases where the greatest strength or corrosion resistance are not required, secondary alloys can sometimes be employed with economy, depending on the relative market values of secondary and virgin metals. It is also to be remembered that the greater material cost for light metal is generally



counterbalanced by the lower cost of fabrication, especially of machining. In favourable cases, the saving in fabricating cost outweighs the greater cost of the metal, so that the finished light-metal part may be cheaper than an iron or steel part previously used.

In applications where a long life is not in question, such as in aircraft or motorcars, the high scrap value is an economic advantage and may normally be expected to bring about half the price of new metal. This high scrap value also applies to the manufacturing scrap, so that careful storage and avoidance of contamination by foreign metals or other aluminium alloys is worth while.

In the chemical and food processing industries, the non-poisonous nature of the light metals and their salts, as well as the colourless character of their corrosion products, is of great advantage, as spoilage of the material in process due to contact with corrosion products need not be feared. For this reason, aluminium continues to come more and more widely into use as a packaging material. On the other hand, as it has no antiseptic action, the light metals do not kill bacteria. Owing to this, the occasional cuts and scratches that occur in the working with the light metals may more readily become infected or inflamed. Appropriate first aid treatment by application of, or bathing in, a suitable antiseptic solution, such as a 1 : 1000 solution of Rivan oil with  $\frac{1}{4}$  of 3 % hydrogen peroxide, is to be recommended, and will completely obviate any infection. For inflamed punctures which may have been caused by the penetration of metal particles in the skin, an ointment to the following pharmaceutical prescription is recommended

R	Liquor alumin. aceto-tartaricum	5.0
	Balsamum Peruvianum	10.0
	Adeps lanae hydrosus	10.0
	Pasta zinci salicylicum	100.0

These recommendations are the result of experience and tests at a number of Swiss aircraft factories.

## 2. APPLICATION OF THE LIGHT METALS

The conditions of service will determine the most suitable alloy. For application under conditions of high static stress, alloys of maximum hardness after full precipitation hardening are the most suitable, even though their elongation in this condition is on the low side. On the other hand, for impact, or rapidly fluctuating loads, alloys of high toughness and elongation are preferred, although they would have a lower proof stress and tensile strength. For such applications, wrought alloys are preferable to castings. In recent years the heat-treatable Al-Cu-Mg (Duralumin type) alloys have

been appreciably improved by artificial or warm ageing, with which a proof stress of 25 to 28 tons/sq. in. (56000 to 63000 lb/sq. in.), a tensile strength of 30 to 33 tons/sq. in. (67000 to 74000 lb/sq. in.) and an elongation of 10 to 14% are obtainable in sections. The warm ageing Al-Zn-Mg alloy, also in the form of sections, shows a proof stress of 32 to 35 tons/sq. in. (72000 to 79000 lb/sq. in.), a tensile strength of 35 to 38 tons/sq. in. (79000 to 85000 lb/sq. in.) and an elongation of 8 to 12%.

For applications not subject to maximum stress conditions, the cheaper non-heat-treatable alloys are used, and castings are often used in preference to wrought parts. In the case of the warm ageing alloys, these are often used in the semi-hard quality, i.e. solution heat-treated only, for conditions of fluctuating stress, owing to their greater toughness in this condition, while for purely static loading, the fully heat-treated alloy (solution heat-treated and warm aged) is used instead.

Careful consideration should also be given to the surface treatment of light metal parts. In the first place, impurities due to contamination by foreign metals must be avoided, as these might give rise to corrosion by galvanic action. Owing to the high impermeability of the natural oxide film on aluminium to gases and liquids, its natural surface requires less upkeep than for iron or steel. When an anodic film or paint is used to give a very high resistance to corrosion, these coatings have a much greater durability than protective coatings on iron or steel. When the metal is used in contact with liquids, it is important that these should not contain foreign metal ions in solution, as, owing to the strongly electronegative character of aluminium, the foreign metal is likely to be precipitated in the metallic state by electrochemical replacement, and galvanic corrosion may then follow. Copper, nickel and lead salts are particularly harmful in this respect whenever they occur in the water supply. Aluminium alloys have a smaller susceptibility to corrosion than magnesium alloys, and corrosion protection is of more importance for magnesium. The lower modulus of elasticity of magnesium requires that sections of greater moment of inertia are used in magnesium structures than in aluminium ones, so that in spite of a lower specific gravity, it is not always possible to save weight by using magnesium as compared with aluminium. The principle applications of magnesium alloys are for castings and forgings in aircraft, in cases where the thickness of the part permitted by the allotted weight is too small to allow of manufacture in aluminium.

In designing a light-metal structure, one of the most important matters is to make allowance for the smaller modulus of elasticity and the resulting lower rigidity by increasing the moment of inertia of the sections. In castings, especially, the rigidity should not be augmented by a simple increase in thickness, as this gives rise to coarser grain size in the casting and a

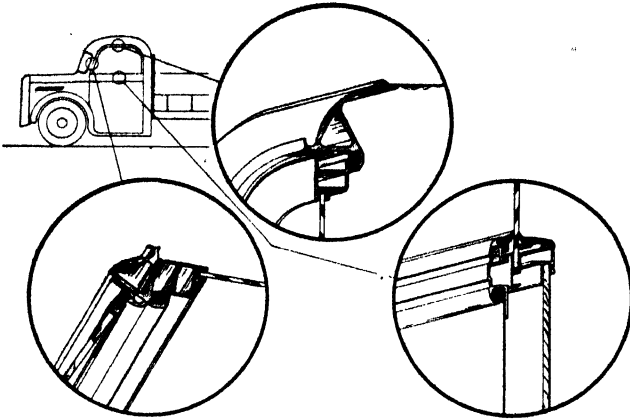


Fig. 394. Use of special sections in motor bodies (after Dr. KOENIG).

lower specific strength. The casting should therefore always be made with thin walls, and the required rigidity should be imparted by the incorporation of suitable ribs. Light metal sections are nearly always produced on the extrusion press, which permits the production of sections with numerous webs and flanges, so that not only can the desired rigidity be readily obtained, but assembly can be simplified, as illustrated in Fig. 394. In many cases also, the strength of the section as a long compression member is increased by making the junctions of the webs thicker as shown above.

Although the lower modulus of elasticity of the light metals is disadvantageous to the strength of long compression members, it is on the other hand an advantage as compared with steel in conditions of suddenly applied overloads, as this property permits a greater deformation to be withstood in the elastic range against greater shock loads. Fig. 395 shows a railway passenger coach built entirely of aluminium alloy, which was in the railway station at Hellem in a bombing attack, in the course of which a steel goods

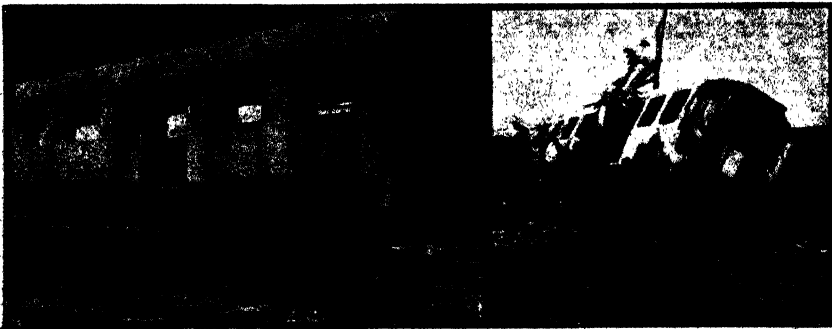


Fig. 395. Aluminium alloy railway passenger coach after damage in an air raid.  
(Courtesy of l'Aluminium Français S.A., Paris.)

waggon was blown against it. The goods waggon, which was burnt out, tilted the light metal bogie coach by the force of the explosion until it came to rest against a vehicle beyond. The side of the passenger coach against which the goods wagon was blown was only slightly damaged.

When a corrosive condition has to be met, the alloy chosen must be suitable for this. In general the alloys containing copper and zinc have a lower resistance to corrosion than alloys which are not composed with these metals. If, however, zinc is present as a compound with magnesium in aluminium alloys, the corrosion resistance is improved, although these alloys have a tendency to be affected by stress corrosion, unless other additions are made and suitable thermal treatments are applied which improve them in this respect. Furthermore, the copper-containing aluminium alloys are much improved by the correct heat-treatment. The Al-Si-Mg alloys show the best resistance to corrosion after heat-treatment, as well as the Al-Mg alloys provided the copper content is kept very low and the material is free from surface imperfections.

### 3. FORMING TO SHAPE

In selecting the process of forming, the conditions of service of the product and the number of pieces required have to be considered. For static duties, castings are often to be preferred, sand castings for small quantities, gravity die castings for moderate quantities, and pressure die castings for large quantities. Sand castings have the highest cost of production of the three types, gravity die castings are distinctly cheaper, and pressure die castings can often be assembled without any machining. The size of piece obtainable in pressure die casting depends on the die casting machines available and from the latest American machines may attain 56 lbs in weight, while for gravity-die and sand castings the size of piece obtainable is unlimited. For conditions of dynamic loading, the alloy chosen should be tough and one with a high elongation, and wrought material is the most suitable. For complicated shapes, forgings can be used, which can be forged under a plain hammer for small quantities or produced as drop-forgings for larger quantities. Just as die castings have a higher degree of accuracy to size than sand castings, so also are drop-forgings more accurate than hammer-forgings and are thus more economical for further manufacture.

In the machining of forged and extruded material, it must be remembered that the fibre structure should be cut into as little as possible, otherwise the part will be weakened against dynamic stresses. If the machining that has to be done on the article is extensive, this also affects the choice of alloy, and the power consumption and tool life are both more favourable on the Al-Mg and Al-Si-Mg alloys than on the Al-Cu-Mg and Al-Si alloys.

In heat-treatable alloys, the tool life in the semi-hard (solution heat-treated) condition is higher than in the fully age-hardened condition, so that from this standpoint, it is preferable to carry out the machining prior to the final precipitation hardening. As regards plastic deformation of the alloys, the Al-Si-Mg are the easiest to form, while the Al-Mg alloys require the greatest force in their deformation.

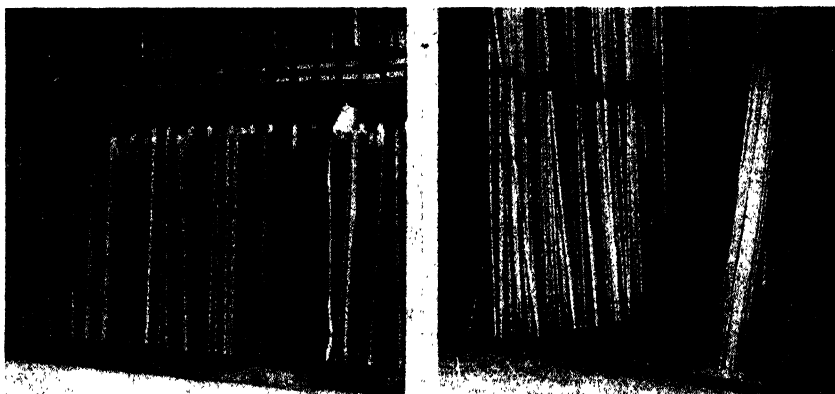


Fig. 396. Storage racks for aluminium sheets and sections.

#### 4. STORAGE OF LIGHT METAL PRODUCTS

In spite of the high corrosion resistance of the light metals, care is needed that storage conditions are satisfactory. Condensation of moisture on the metal is harmful, as well as contact with damp concrete, sawdust concrete, asbestos compounds and impregnated wood. Light metals should not be packed until they have come to room temperature. If, in winter, very cold sheets are packed in a warm room, water from the atmosphere will condense on them, which only disappears slowly from surfaces in close contact and gives rise to a galvanic effect due to differential aeration which may in some cases lead to corrosive staining of the surface. For greatest assurance against corrosion, light alloys should be oiled or greased before dispatch, using acid-free oils or greases — bone oil or a mixture of anti-corrosion oil such as M4\* being suitable. Before subsequent painting, thorough degreasing is necessary. The store should be dry, well ventilated, dust-free and maintained at as uniform a temperature as possible. Sheets and sections are better stored vertically as in Fig. 396 than horizontally; only thin sections where there is a danger of kinking should be stored

\* Shell Dromus oil B (Shell Company, London).

horizontally on wood bearers. For long periods in storage, a periodic inspection of the material is recommended, since excessive temperature changes in storage may cause condensation. For the transport of sheets, it is important that no particles of extraneous matter are between the sheets when packed. Owing to the vibration of sheets in transit, such particles of foreign matter become pressed into the surface and give an unsightly appearance, like corrosion, wherever they occur.



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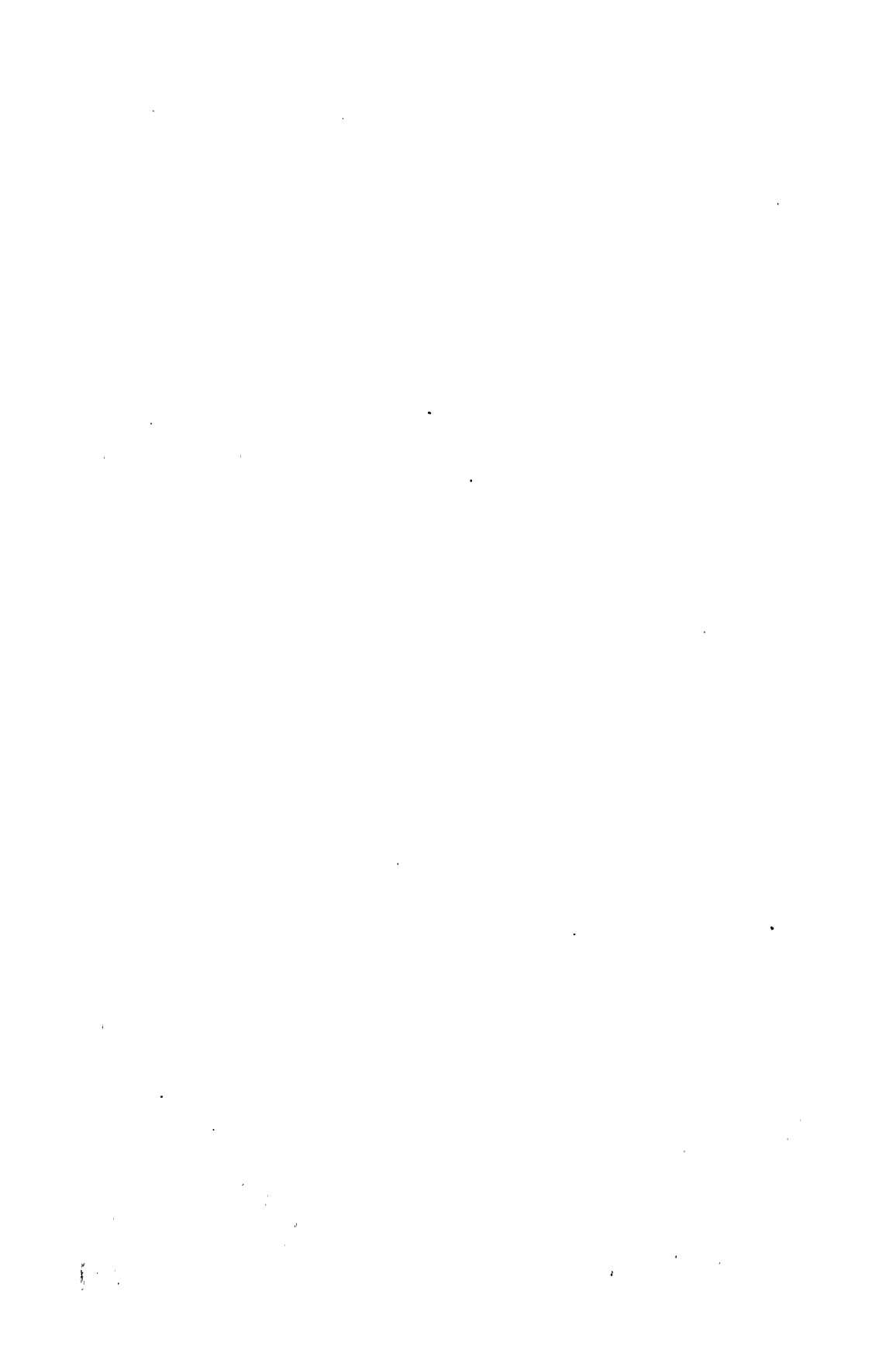
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